

INTRODUCTION TO SOLID-STATE LIGHTING

Artūras Žukauskas
Michael S. Shur
Remis Gaska



INTRODUCTION TO SOLID-STATE LIGHTING

Artūras Žukauskas

Vilnius University

Michael S. Shur

Rensselaer Polytechnic Institute

Remis Gaska

Sensor Electronic Technology, Inc.



A Wiley-Interscience Publication

JOHN WILEY & SONS, INC.

This text is printed on acid-free paper. (∞)

Copyright © 2002 by John Wiley & Sons, Inc., New York. All rights reserved.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4744. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012, (212) 850-6011, fax (212) 850-6008, E-Mail: PERMREQ @ WILEY.COM.

For ordering and customer service, call 1-800-CALL-WILEY.

Library of Congress Cataloging-in-Publication Data Is Available

ISBN 0-471-21574-0

Printed in the United States of America.

10 9 8 7 6 5 4 3 2

... when touched, the light will split into an infinite amount of small lights that will come down the hill and spread over your homes ...

Jonas Biliūnas, Lithuanian writer
“Light of Happiness” (1905)

PREFACE

Breakthroughs in artificial light sources—a piece of burning wood “invented” more than 500,000 years ago, gas lighting (1772), electric lighting (1876), and fluorescent lamps (1938)—have led to the development of modern lighting sources. These sources are tungsten incandescent and compact fluorescence lamps for residential use, fluorescence lamps for work environments, and sodium lamps for street lighting. Today, 21% of electric energy use is in lighting, and perhaps half of this energy could be saved by switching to efficient and cold solid-state lighting sources. Projected cumulative financial savings from solid-state lighting might reach \$115 billion by year 2020. Solid-state lighting will use visible and ultraviolet LEDs that are expected to reach lifetimes exceeding 100,000 hours. At present, LEDs are the most efficient sources of colored light in almost the entire visible spectral range. White phosphor conversion LEDs already surpassed incandescent lamps in performance, and their efficiency is expected to triple by the year 2010. From traffic lights to road signs, from automobile taillights to outdoor displays, from landscape to accent lights, solid-state light sources that are harbingers of the next lighting revolution have already arrived.

Semiconductor physicists, chemists, materials scientists, opticians, lighting engineers and business administrators work jointly on solid-state lighting so that humankind can reap the benefits of this exciting technology. Various issues of bright semiconductor lamps have been described in the scientific literature. Modern LEDs based on AlGaAs, AlGaInP, and AlInGaN semiconductors are described in the collections of articles edited by Stringfellow and Craford (1997) and by Mueller (1999a). Nakamura and Fasol (1997) and Nakamura and Chichibu (2000) reviewed blue AlInGaN-based light emitters that are the most recent achievement

layer is often considered as parasitic. Therefore, thin active layers (homogeneous or comprised of multiple wells) are often preferred. An optimum active-layer thickness involves a trade-off between active-layer reabsorption and electron confinement and depends on the emission wavelength (Gardner *et al.* 1999).

5.2. PHOTONICS OF PLANAR RECTANGULAR HIGH-BRIGHTNESS LEDs

The design of high-brightness LEDs is aimed at the high efficiency of light extraction and uses the escape-cone concept and low-parasitic-loss approaches (Stringfellow and Craford 1997). Cost pressures (Craford 1996) result in diverse schemes for commercial high-brightness LEDs utilizing different material systems. In this section we discuss the designs of practical AlGaAs, AlGaInP, and AlInGaIn high-brightness LEDs that are manufactured using conventional planar rectangular technologies.

5.2.1. AlGaAs Red LEDs

Steranka (1997) described the photonics of practical AlGaAs LEDs. As we mentioned in Section 4.2.2, the main advantage of an AlGaAs/GaAs materials system is a very small lattice mismatch (lattice constants of GaAs and AlAs differ by less than 0.2% at 25°C). This makes feasible the growth of high-quality AlGaAs films on GaAs substrates. Thick and transparent layers (with high Al content) that are required for opening the lateral escape cones are easily produced using liquid-phase epitaxy (LPE) (Rupprecht *et al.* 1967).

Starting with the introduction of a thick window layer to improve light extraction in a single-heterostructure (SH) AlGaAs LED by Nishizawa *et al.* (1977), the quantum efficiency of the device was gradually increased (Varon *et al.* 1981, Nishizawa *et al.* 1983). Although an SH-AS version of the LED is still available, it exhibits moderate performance comparable to that of a red-filtered incandescent lamp. Implementation of a double heterostructure (DH) and transparent substrate by Ishiguro *et al.* (1983) and Cook *et al.* (1988) led to 21% external quantum efficiency (Ishimatsu and Okuno 1989). Since the internal quantum efficiency in AlGaAs is ~80% (Steranka *et al.* 1995), this value for the external quantum efficiency is close to the highest value obtainable in a six-cone design. Therefore, the design of AlGaAs red LEDs has undergone no significant improvements ever since.

Figure 5.2.1 shows two basic designs of commercial high-brightness AlGaAs LED chips with a DH active layer. The active layer is sandwiched between the wide-bandgap cladding layers. A version of a DH-AS LED is depicted in Fig. 5.2.1a. Figure 5.2.1b presents the design of a DH-TS LED. In the latter case, the GaAs substrate is removed by selective etching, and a patterned back contact is deposited.

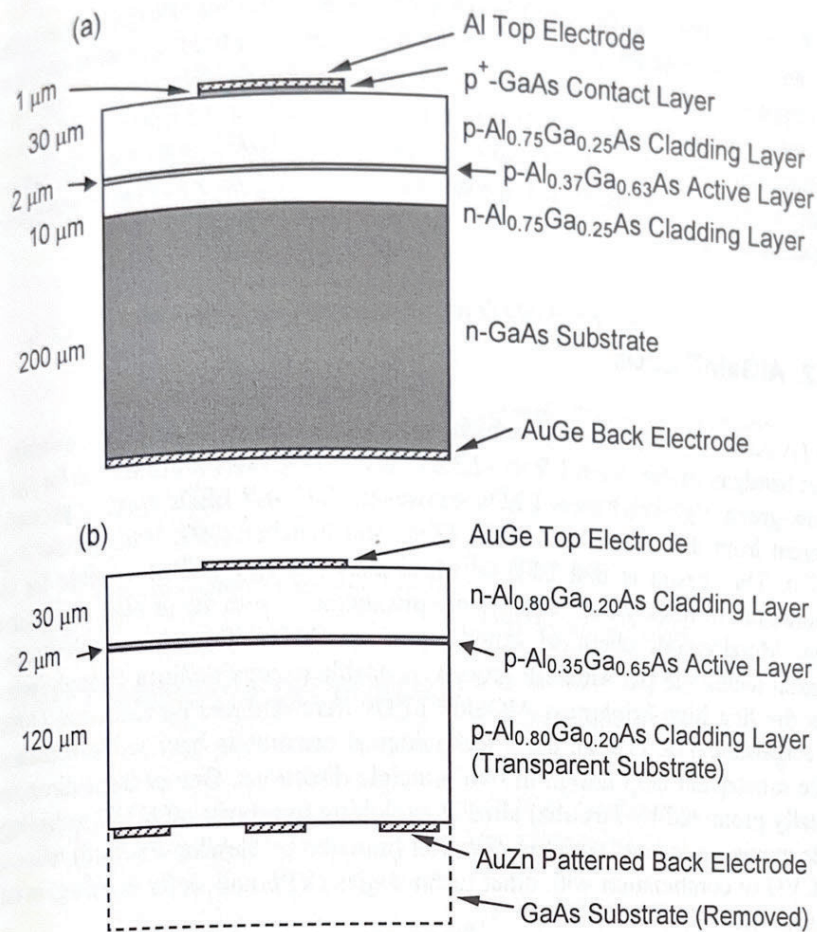


FIG. 5.2.1. Typical chip structures of high-brightness AlGaAs double-heterostructure LEDs: (a) absorbing substrate (DH-AS) LED; (b) transparent substrate (DH-TS) LED. (After Steranka 1997.)

The attainable thickness of the high-quality upper window layer is about 30 μm . This may be insufficient for complete opening of the upper lateral semi-cones. Other losses occur because of shielding of the vertical escape cones by the contacts. Photon absorption in the ohmic region, produced by metallization, is due mainly to the amorphous nature of the crystal in this region (Lee 1998a). The shielding extends over a significant area, since the top contact must be at least of 80 to 100 μm in diameter for high-speed wire bonding and the patterned back contact covers about 30% of the surface. With these losses taken into account, our estimate of the extraction efficiency in a TS LED for a typical chip width of 210 μm is about 19%, which is somehow lower than that observed. The actual light extraction efficiency is probably increased due to the randomization of photon trajectories at the chip walls formed by sawing (Schnitzer *et al.* 1993a, Lee 1998a).

Since the radiant efficiency in AlGaAs decreases for wavelengths shorter than 700 nm (because of the proximity of the direct-gap to indirect-gap crossover), the highest luminous efficiency is achieved around 650 nm (Nishizawa *et al.* 1983). At this wavelength, the 21% external efficiency yields a 15-lm/W performance. Commercial AlGaAs LEDs exhibit somewhat lower performances, around 10 lm/W (Craford 1997), which are still three times higher than that of red-filtered incandescent lamps.

5.2.2. AlGaInP LEDs

The $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ alloy, which is lattice matched to GaAs and exhibits a direct bandgap in the range 1.9 to ~2.3 eV, is the most favorable material for red to yellow-green high-brightness LEDs. However, AlGaInP LEDs employ photonics different from that of AlGaAs LEDs (Kish and Fletcher 1997, Vanderwater *et al.* 1997b). The reason is that LPE or vapor-phase epitaxy (VPE) suitable for the manufacture of thick window layers are incompatible with the growth of AlGaInP alloys. Metalorganic chemical vapor deposition (MOCVD), which is the mature epitaxial technique for AlGaInP growth, is unable to provide thick enough layers. After the first high-brightness AlGaInP LEDs were reported by Kuo *et al.* (1990) and Sugawara *et al.* (1991), these technological constraints have led to branching of the subsequent chip design in two principle directions. One of these directions (initially promoted by Toshiba) aims at exploiting thin-layer MOCVD technology to the maximum extent. Another direction (initiated by Hewlett-Packard) relies on MOCVD in combination with other technologies (VPE and wafer bonding) to implement thick window layers.

The first Toshiba AlGaInP LED comprised a DH grown on an absorbing GaAs substrate. The DH was capped with a lattice-matched $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ low-resistivity CSL, which was transparent to emission light and also served as a WL. Furthermore, an *n*-type AlGaInP CBL (Sugawara *et al.* 1992a,b) was introduced. The CBL does not allow current to enter the DH underneath the top contact. Hence, this layer addresses two important issues of light extraction. First, shielding of the upward escape cone is minimized. Second, the lateral semicones are less truncated by the thin WL, since light generation is shifted to the peripheral area of the chip. The photonic design of thin-layer AlGaInP LEDs was completed by adopting a DBR (Sugawara *et al.* 1992a, 1993; Itaya *et al.* 1994) (Fig. 5.2.2a). We estimate that this design utilizes up to three effective escape cones and the light-extraction efficiency may reach 12% for one-pass escape (again, the actual efficiency is somewhat higher, owing to sawed walls and multiple reflections between the top surface and the DBR).

Further development of this kind of LED involved optimization of the DBR structure (Sugawara *et al.* 1994b, Chang *et al.* 1997a, Chiou *et al.* 2000), an attempt to introduce a transparent contact (Lin *et al.* 1994b, Aliyu *et al.* 1995), and thinning the active layer using a multiple-quantum-well (MQW) structure (Chang *et al.* 1997b, Chang and Chang 1998a, Li *et al.* 1999). Quantum efficiencies

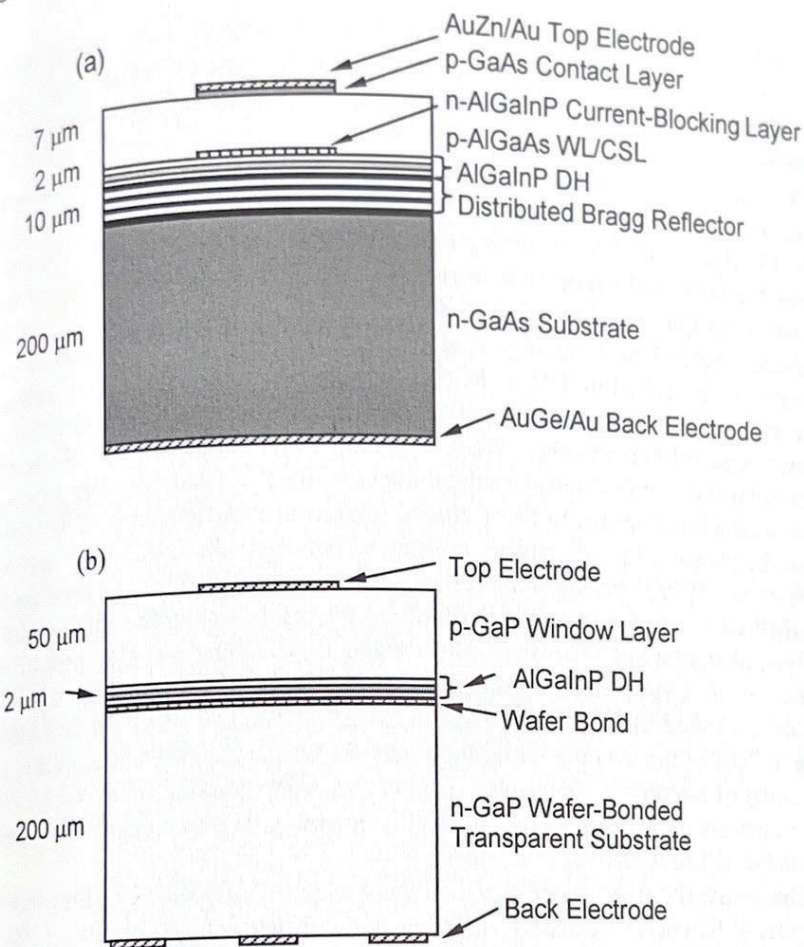


FIG. 5.2.2. Typical chip structures of high-brightness $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ LEDs: (a) DBR LED with a current-blocking layer; (b) TS LED with a wafer-bonded transparent substrate. (After Kish 1997.)

as high as 7% at 610 nm (orange, 24 lm/W) (Itaya *et al.* 1994) and 5% at 590 nm (amber, 26 lm/W) (Chiou *et al.* 2000) were reported for AlGaInP DBR LEDs.

The approach developed by Hewlett-Packard is based on using thick, conductive (heavily doped) GaP windows (Fletcher *et al.* 1991) that are transparent throughout the red to yellow-green spectral regions, where AlGaInP is an efficient light emitter. Although GaP has a 3.6% lattice mismatch to $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{In}_{0.5}\text{P}$ layers, the network of dislocations that occurs at the interface does not penetrate into the DH and the LED reliability is preserved. MOCVD allows for high-quality GaP layers of only up to 15-μm thickness to be grown over AlGaInP. The resulting WL is too thin to open the lateral escape cones completely. The implementation of combined technologies led to the elimination of this shortcoming. Following the MOCVD growth of an AlGaInP DH on the absorbing GaAs substrate, a

GaP WL/CSL as thick as $63\text{ }\mu\text{m}$ was grown by hydride vapor-phase epitaxy (HVPE). This resulted in light extraction through three escape cones (Fig. 5.1.2c), and LEDs with an external quantum efficiency of 6% ($\sim 20\text{ lm/W}$) in the range 590 to 620 nm were fabricated (Huang *et al.* 1992).

Kish *et al.* (1994a) implemented a thick GaP TS in order to exploit the rest of the escape-cone family. Figure 5.2.2b shows a typical design of a practical six-cone AlGaInP chip. The absorbing GaAs substrate is removed from the grown hybrid AlGaInP/GaP structure by means of conventional selective chemical etching, and a transparent GaP wafer is fused instead to the revealed AlGaInP DH. The wafers are bonded by annealing at elevated temperatures under applied uniaxial pressure (Liau and Mull 1990). In this way, optical coupling of the wafers is achieved. However, implementation of a reliable interface with low electrical resistance required considerable effort. Matching of the orientation of the bonded surfaces (while simultaneously maintaining rotational crystallographic alignment of the wafers) was shown to be of crucial importance for the electrical properties required, irrespective of lattice mismatch between the AlGaInP and GaP (Kish *et al.* 1995, Vanderwater *et al.* 1997a). Bonding of large-diameter AlGaInP/GaP structures with mechanical strength exceeding that required for manufacturing LED chips was adopted for large-scale production (Höfler *et al.* 1996, Maranowski *et al.* 1997). The bond exhibits high reliability with the projected lifetime of the LED in excess of 120,000 hours for degradation down to 70% of the average initial light output (Kish *et al.* 1996). The quality and uniformity of bonding were characterized via scanning acoustic microscopy, white light transmission measurements, full-wafer mapping of parametric performance, and operation life tests (Tan *et al.* 2000).

Due to the six escape cones opened, the AlGaInP/GaP DH-TS LEDs exhibited luminous efficiencies (external quantum efficiencies) of 50.3 lm/W (13%) at 607 nm and 35.5 lm/W (24%) at 637 nm (Kish *et al.* 1996, Maranowski *et al.* 1997). High-power LED lamps based on AlGaInP/GaP DH-TS structures were demonstrated. A monolithic LED bar ($375 \times 4500\text{ }\mu\text{m}^2$) exhibited a luminous flux of 84 lm at 610 to 615 nm (Kish *et al.* 1994b). However, the device suffered a threefold decrease in extraction efficiency because of the truncation of the side escape cones and a 40% efficiency decrease due to heating. A somewhat smaller lamp with a $500 \times 500\text{ }\mu\text{m}^2$ junction area with improved thermal resistance emitted 10 to 20 lm of flux while maintaining luminous efficiencies exceeding 20 lm/W (Höfler *et al.* 1998).

The versatility of the combined technology made different kinds of light-escape structures feasible. A four-cone chip was fabricated by bonding a thick GaP window on the top of the AlGaInP DH with the subsequent removal of the GaAs absorbing substrate (Chang *et al.* 1996). The thick window substitutes for the substrate and allows one to avoid handling thin epitaxial layers. Zeng *et al.* (1998) reported on the elimination of the wafer bonding process in fabrication of the DH-TS LED. After the GaAs substrate was removed from the AlGaInP/GaP structure, the lower GaP window was grown by HVPE. Wafer bonding of mirror substrates (AuBe/glass: Horng *et al.* 1999a and Au/AuBe/SiO₂/Si: Horng *et al.* 1999b) to the

top of the MOCVD-grown AlGaInP DH with subsequent removal of the GaAs substrate was also demonstrated.

Of recent improvements in planar rectangular AlGaInP LEDs, the most significant is replacement of the DH by a multiple-well heterostructure (MWH) that resulted in reduced thickness of the active layer (Chang and Chang 1998b, Gardner *et al.* 1999). The MWH-TS LED exhibited luminous efficiencies (external quantum efficiencies) of 74 lm/W (24%) at 615 nm and 54 lm/W (32%) at 632 nm that to date are the highest values reported for escape-cone planar rectangular LEDs.

Record-performance AlGaInP LEDs are fabricated using a nonrectangular device shape. These LEDs are described in Section 5.3.1.

5.2.3. AlInGaN LEDs

The $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloy has a direct bandgap which varies from 1.9 to 3.4 eV, depending on the In molar fraction, whereas Al-containing nitride alloys can be used for wide-bandgap cladding layers. This allows one to fabricate high-brightness LEDs that cover the spectral range from red to near UV. At present, an AlInGaN materials system offers the most efficient LEDs in the blue-to-green region. AlInGaN-based blue, violet, and near-UV LEDs are indispensable for the fabrication of white LEDs, which operate by radiation down-conversion in phosphors (see Chapter 6).

As discussed in Section 4.2.4, for many years, development of group III nitride materials was hindered by the lack of a suitable substrate. In spite of this, a mature technology for MOCVD growth of nitrides over substrates that are mismatched in lattice constants and coefficients of thermal expansion was developed by using low-temperature buffer layers. The substrate used most extensively is sapphire (Al_2O_3). Light-emitting AlInGaN structures have also been grown on 6H-SiC (Kuga *et al.* 1995) and spinel (MgAl_2O_4 ; Kuramata *et al.* 1995, Khan *et al.* 1997). Fortunately, all these substrates are transparent to the light generated in blue and green LEDs.

Since the transparent substrate is the inherent component of most AlInGaN light-emitting structures, the very first high-brightness blue AlInGaN DH LED introduced by Nichia (Nakamura *et al.* 1994a) featured an efficient light-extraction design. The photonic design underwent minor improvements in subsequent development of blue-green DH LED (Nakamura *et al.* 1994b), blue-violet, blue, green, amber, and red single-quantum-well (SQW) LEDs (Nakamura *et al.* 1995a,b,c, Mukai *et al.* 1999), and blue and green MQW LEDs (Koike *et al.* 1996, Kozodoy *et al.* 1997, Lester *et al.* 1998) on sapphire substrate. Figure 5.2.3a shows a typical chip design for a practical AlInGaN/ Al_2O_3 LED. The thin emitting structure (DH or SQW) is sandwiched between *n*- and *p*-GaN contact layers. A thin transparent-metal layer is used for current spreading. This design is similar to that of an AlGaAs TS LED (Fig. 5.2.1b), the difference being that the

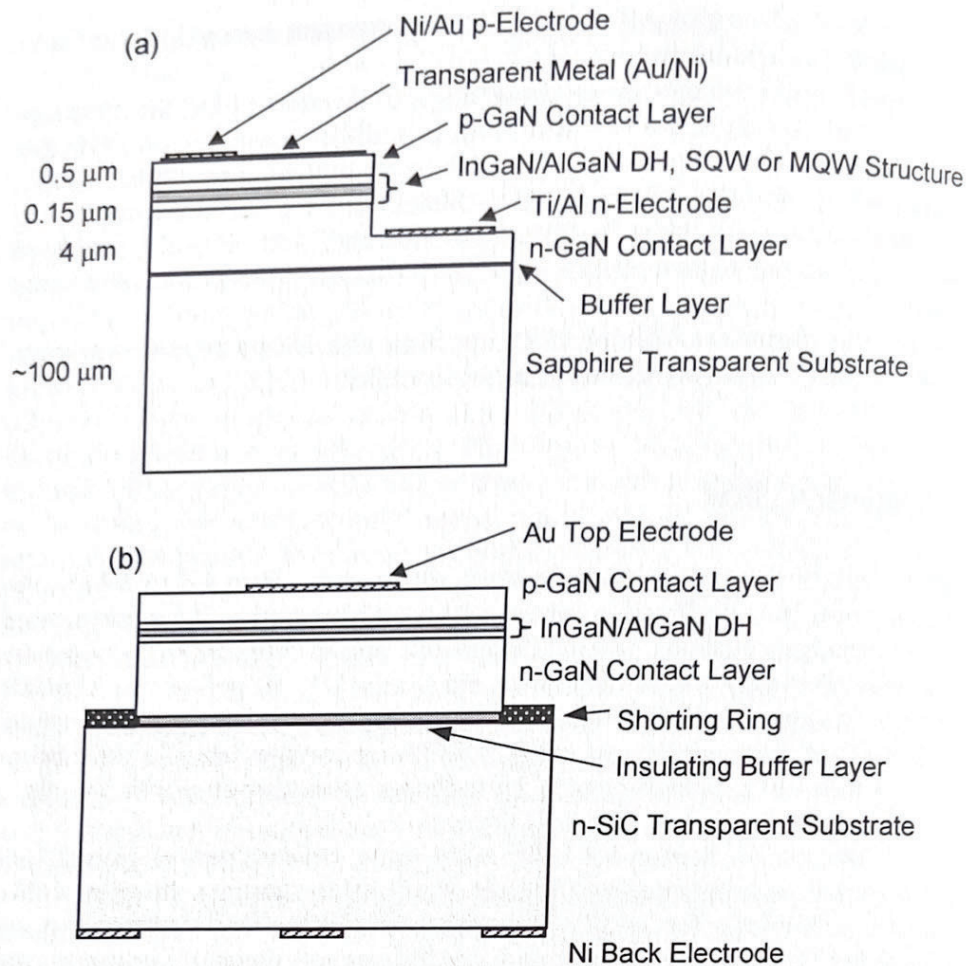


FIG. 5.2.3. Typical chip structures of TS AlInGaN-based LEDs: (a) AlInGaN/Al₂O₃ LED (after Nakamura and Fasol 1997); (b) AlInGaN/SiC LED (after Edmond *et al.* 1997b).

n-electrode is exposed upward (by means of etching a mesa) because of the insulating substrate. However, the TS concept, which was described in Section 5.1.1, is to be reconsidered for AlInGaN/Al₂O₃ LEDs (Lee 1998b), as discussed below.

As mentioned in Section 5.1.1, the extraction efficiency for AlInGaN LEDs grown on TS is much higher than the efficiency for AlGaAs and AlGaInP LEDs. First, the refractive index of AlInGaN materials ($n_s \approx 2.5$) is smaller than that of GaAs and GaP. Therefore, about 9.2% of the photons emitted can escape through the upward cone with the apex of $2\theta_{c1}(n_s, n_e) \approx 74^\circ$ (see Fig. 5.2.4). Second, the transparent sapphire substrate has even a smaller refractive index ($n_i = 1.78$), which satisfies the condition $n_e < n_i < n_s$. This results in a larger apex of the

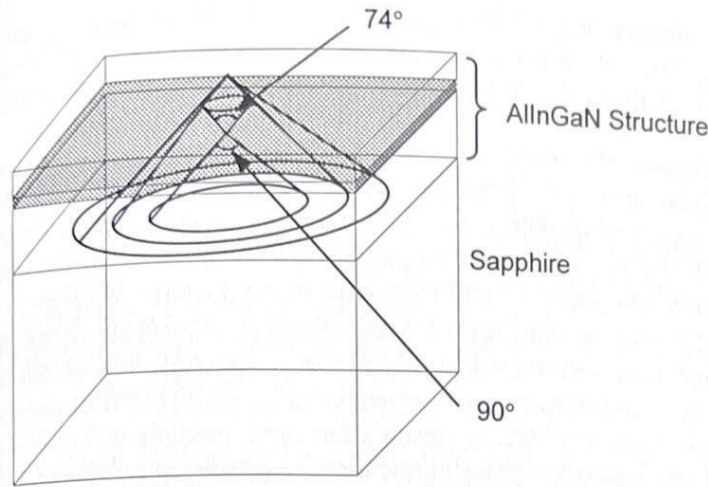


FIG. 5.2.4. Escape cones in an AlInGaN-based LED chip on sapphire substrate. The apex of the upward cone is 74° and the apex of the inner downward cone is 90° . The downward subconical structure with the ring base (inner apex 74° and outer apex 90°) supplements the upward cone to a full escape cone with an apex of 90° .

downward cone $2\theta_{c2}(n_s, n_i) \approx 90^\circ$. A new feature of this asymmetric system is that photons that undergo total internal reflection from the upper surface within the range of angles $\theta_{c1} < \theta < \theta_{c2}$ can escape to the substrate through a subconical structure with an outer apex of $2\theta_{c2}$ and an inner apex of $2\theta_{c1}$, as shown in Fig. 5.2.4. The upward cone and the subconical structure supplement each other; thus a second full escape cone with an apex of $2\theta_{c2}$ occurs. It should be noted that the photons escape from the sapphire to the epoxy through a downward cone and four lateral semicones with apexes of $2\theta_{c3}(n_i, n_e) \approx 115^\circ$ (not shown in Fig. 5.2.4). These five cones overlap completely, so that all photons may escape from the sapphire to the epoxy.

Owing to thin semiconductor layers used in this structure, Fresnel losses in the vertical-cone chip are negligible, since the majority of the photons reflected may escape on the second and third passes. Consequently, the light extraction efficiency is given by two coupled (i.e., lossless) cones with an apex of $2\theta_{c2}$ and Fresnel losses for the epoxy–air interface:

$$\eta_{\text{opt}} = \frac{4n_e}{(n_e + 1)^2} \left[1 - \sqrt{1 - (n_i/n_s)^2} \right] \approx 0.29. \quad (5.2.1)$$

This efficiency is larger than that for a six-cone design in GaAs/GaP-based chips. Even higher efficiency is expected if some light can escape from the semi-

conductor structure in the lateral direction (Lee 1998b). However, this path requires multiple (~ 100 in average) reflections within the structure. Even for active layers of ~ 30 Å thickness, the absorption losses are too high for this path to contribute.

Another type of practical AlInGaN LED structure is grown over a 6H-SiC substrate (DenBaars 1997; Edmond *et al.* 1997a,b; Adivarahan *et al.* 2001). SiC has the advantage of smaller lattice mismatch, and the use of SiC substrates leads to improved quality of the nitride materials. However, the AlInGaN/SiC LEDs (Fig. 5.2.3b) might have somewhat lower light extraction efficiency than the AlInGaN/Al₂O₃ LEDs. The reason is that the refractive index of SiC ($n_i = 2.7$; Ninomiya and Adachi 1994) is higher than that of AlInGaN. Almost all the downward-directed emission from the semiconductor structure (50% of the total emission) may penetrate into SiC substrate after some multiple reflections (no total internal reflection occurs). Actually, the device operates in a four-cone regime as shown in Fig. 5.1.2d. However, the three cones in the SiC TS (one downward cone and four lateral semicones) allow only 11.5% of the photons emitted to escape because of the high refractive index of SiC. With the upward escape cone (coupled with the downward one) taken into account, the total light-extraction efficiency is about 0.21, which is somewhat smaller than that of AlInGaN/Al₂O₃ LEDs.

The reported luminous efficiency (external quantum efficiency) of top-emitting devices on a sapphire substrate is 7 lm/W (14%) for blue (465 nm), 60 lm/W (11%) for green (525 nm), and 21 lm/W (4.5%) for amber (595 nm) (Mukai *et al.* 1999). Even higher efficiencies of AlInGaN/Al₂O₃ LEDs were achieved by exploiting the photonic configuration depicted in Fig. 5.2.4 to the maximum extent. As can be seen in Fig. 5.2.4, a major part of emission in the AlInGaN/Al₂O₃ LED is directed downward. Hence, it is reasonable to flip the chip to reduce losses caused by the built-in reflector contained in the plastic dome. Mass production of *flip-chip* (FC) AlInGaN LEDs was reported by Koike *et al.* (2000). Blue and green AlInGaN FC LEDs are claimed to exhibit 20% external quantum efficiency. Wierer *et al.* (2001a,b) demonstrated a high-power AlInGaN-based FC LED with a large emitting area (0.70 mm^2). The device (see Fig. 5.2.5) emitted at 435 nm and exhibited 21% external quantum efficiency and 20% radiant efficiency with a record light output power of 400 mW.

Despite lower light-extraction efficiency, AlGaIn/SiC LEDs exhibit performances that are similar to that of AlInGaN/Al₂O₃ LEDs or even higher. Typical external quantum efficiencies of commercially available blue AlGaIn/SiC LEDs are 20% ($\sim 15\%$ radiant efficiency).

The present performance of AlInGaN LEDs is not to be considered as ultimate, since the possibilities of an increase in the internal quantum efficiency in AlInGaN have not been exhausted. Furthermore, the light-extraction efficiency can still be improved, since the upper transparent window with two additional escape cones has not yet been exploited. A lot of techniques are shown to possess potential for improvement of the photonics in AlInGaN LEDs. For instance, thick upper WLs may be grown by HVPE (Usui *et al.* 1997, Smith *et al.* 1998) in combination

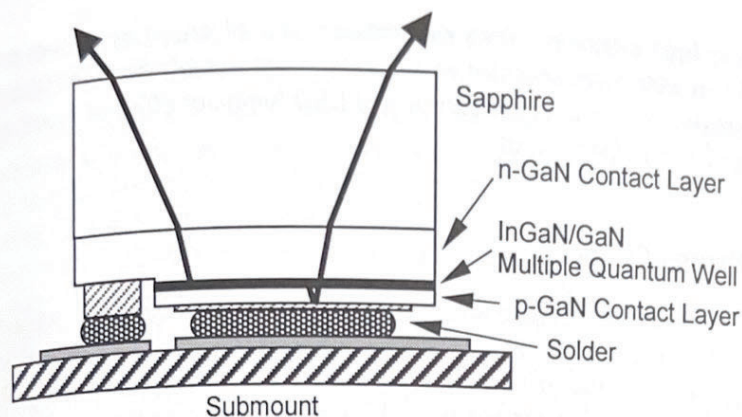


FIG. 5.2.5. Schematic cross section of high-power flip-chip AlInGaN-based LED. (After Wierer *et al.* 2001b.)

with MOCVD. Epitaxial lift-off and bonding of AlInGaN light-emitting structures to host substrates have been explored (Floyd *et al.* 1998; Wong *et al.* 1998, 1999; Song *et al.* 1999a,b). Incorporation of DBR structures in the devices was demonstrated by Song *et al.* (1999b) and Nakada *et al.* (2000). Further improvement in the transparent contacts (Margalith *et al.* 1999, Sheu *et al.* 1999, Huh *et al.* 2000) and introduction of epitaxially laterally overgrown GaN substrates (Kato *et al.* 1994, Mukai *et al.* 1998a, Nakamura 1999) was performed. A SiO₂ CBL was inserted underneath the *p*-electrode of InGaN/GaN MQW LED to improve the light-extraction efficiency by reducing the total area of the top contact (Huh *et al.* 2001). To completely eliminate the top semitransparent electrode and highly resistive *p*-AlGaIn cladding layer, Takeuchi *et al.* (2001) introduced a tunnel junction grown on InGaN/GaN MQW.

New possibilities are offered by molecular-beam epitaxy (MBE) technology (Riechert *et al.* 1997; Grandjean *et al.* 1997, 1998; Grandjean and Massies 1999). New substrates for growth of III-N materials are still being sought. Bour *et al.* (2000) have demonstrated polycrystalline LEDs deposited on quartz substrates. An improved quantum efficiency in LEDs is offered by epitaxial growth of GaN on tetragonal LiAlO₂ substrate in a nonpolar direction (Waltreit *et al.* 2000).

5.3. PHOTON OUTCOUPLING IN NONRECTANGULAR AND NONPLANAR GEOMETRIES

Most practical LED chips are made by planar technologies and employ rectangular geometry. Solution of the light-extraction problem in such chips relies on the concept of escape cones, discussed above. Because of geometrical constraints, the quantum efficiencies of planar and rectangular LEDs are unlikely to exceed values far above 30%. In this section we consider nonrectangular and nonplanar ap-