

Chapter 2

Solid-State Lighting Technology in a Nutshell

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Abstract Solid-state lighting (SSL) is the most promising energy saving solution for future lighting applications. SSL is digital and multi-scaled in nature: SSL is based on the semiconductor-based LED and its packaging technology. The LED module can be obtained by cooperation of electronic devices. By integrating the hardware and software, the luminaire and further lighting system can be achieved. This chapter will describe the key elements of SSL technology as the fundamental information towards SSL reliability.

2.1 Introduction

Light technologies are substitutes for sunlight in the 425–675 nm spectral regions where sunlight is most concentrated and to which the human eye has evolved to be most sensitive.

Three major light sources have much different principles:

- Incandescence lamp: The tungsten filament is heated by electric current until it glows and emits light.
- Fluorescent lamp: Mercury atoms are excited by an electric arc and emit UV radiation, and such radiation will strike the phosphor coating inside the glass tube, where the UV light will be converted into visible light.

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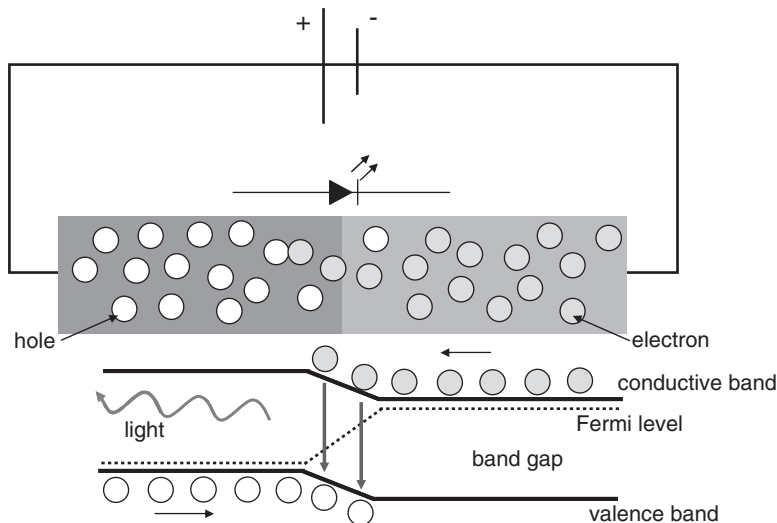


Fig. 2.1 Working principle of an LED

- Solid-state lighting: LED is a semiconductor diode, where the materials are doped with impurities to create p–n junction (as illustrated in Fig. 2.1). When the LED is powered, electrons flow from n-side (cathode) to p-side (anode). (electrons and holes) flow into the function and form electrodes. When an electron meets a hole, it falls into a lower energy level and releases energy in the form of photons [1]. The specific wavelength emitted by LED depends upon the band gap structure (or materials).

Because the light from SSL is narrowband, and can be concentrated in the visible portion of the spectrum, it has, like fluorescence, much higher light-emission efficiency than incandescence. Unlike in fluorescence technology, the wavelength of the narrowband emission can be tailored relatively easily. Hence, this technology is potentially even more efficient than fluorescence.

Lighting is going through a radical transformation, driven by various societal, economical, and environmental needs and rapid progress of solid-state lighting (SSL) and system-related technologies. The value chain of SSL is illustrated in Fig. 2.2 [2]. SSL begins with semiconductor-based LED technology and its packaging. The multiple LED assembly is obtained to be the basic assembly unit for the LED module and luminaire. The combination of electronics is required to proper drive the lighting function. The SSL-based lighting systems can be achieved by combination of hardware and software.

Three qualitative measurements are usually applied to define the quality of LED lighting:

1. Lighting efficiency, as knows as efficacy, enables the comparison of the efficiency of different types of lighting technology. Efficacy is usually defined by

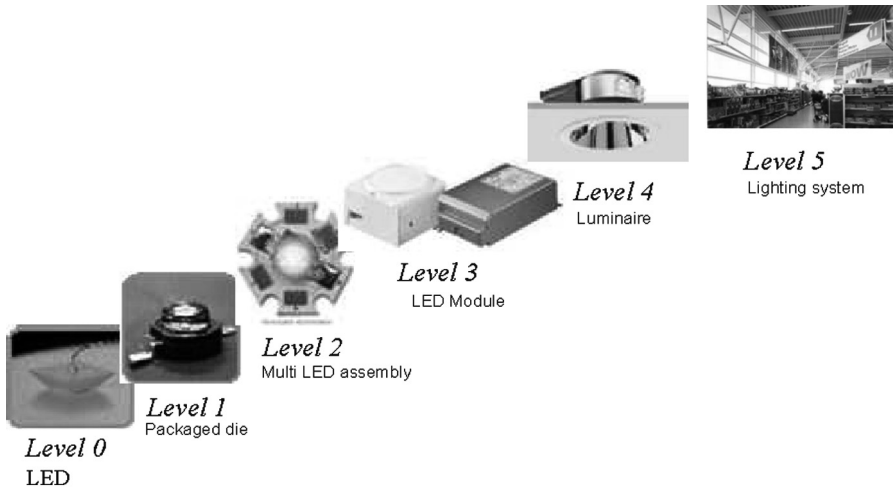


Fig. 2.2 SSL value chain

Table 2.1 Efficacy, CRI and lifetime of common light sources [3]

Light source	Efficacy (lm/W)	CRI	Lifetime (h)
Incandescent (120 V)	14.4	~100	1,000
Compact fluorescent	51	80	10,000
High-pressure mercury	34	50	24,000
High-pressure sodium	108	22	24,000
LED	130–220	>80	50,000

- lumens/watt (lm/W), and light source with higher efficacy refers to high energy efficiency. The luminous intensity of an LED is approximately proportional to the amount of current supplied to the device. The design/process limitation provides the upper boundary on both input current and light intensity.
2. Color rendering index (CRI), is another measurement of the lighting quality. CRI is a quantitative measure of the ability of a light source to reproduce the colors of various objects faithfully in comparison with an ideal or natural light source.
 3. Lifetime is a reliability parameter of the light source. It represents the working time of such light source within the lighting specification.

Table 2.1 presents examples of the overall efficacy for common light source. In the following chapter, the process at each SSL value chain, such as LED chips, LED packages, multi-LED assemblies, LED modules, luminaires, and large SSL systems, will be presented.

2.2 Level 0: LED Chips

2.2.1 Overview

In recent years, high-brightness LEDs have attracted much attention as light sources for various applications, such as LCD backlighting, camera flash light, indoor lighting, and all kinds of outdoor signs. LEDs are semiconductor devices that emit incoherent narrow-spectrum light when electrically biased in the forward direction. The color of the emitted light depends on the chemical composition of the semiconducting material used and can be near-ultraviolet, visible, or infrared. Progress in the development of new materials for LEDs has continued to since the first red light emitting gallium arsenide phosphate (GaAsP) devices were introduced in low volumes in the early 1960s and in high volumes later in the decade. The materials first developed were p-n homojunction diodes in $\text{GaAs}_{1-x}\text{P}_x$ and zinc-oxygen-doped GaP for red-spectrum devices; nitrogen-doped $\text{GaAs}_{1-x}\text{P}_x$ for red, orange, and yellow devices; and nitrogen-doped GaP for yellow-green devices. A milestone was reached in the mid-1980s with the development and introduction of aluminum gallium arsenide (AlGaAs) LEDs, which used a direct band-gap material system and a highly efficient double heterostructure (DH) active region. In 1990, Hewlett-Packard Company and Toshiba Corporation independently developed and introduced a new family of LEDs based on the quaternary alloy material system: AlGaInP.

The luminous efficiency of the different materials of LEDs versus wavelength is shown in Fig. 2.3. The figure indicates that low-power and low-cost LEDs, such as

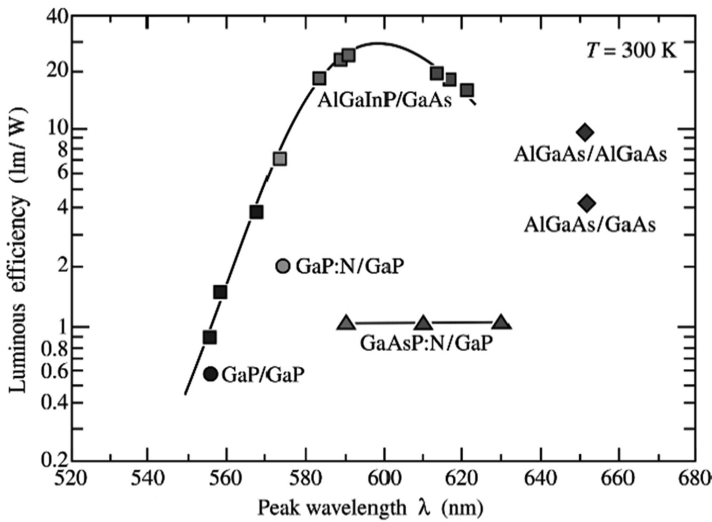
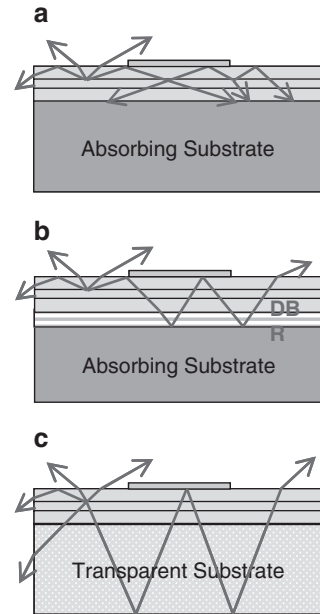


Fig. 2.3 Overview of luminous efficiency of visible LEDs made from phosphide, arsenide, and nitride material system (adopted from United Epitaxy Corp., 1999; updated 2000)

Fig. 2.4 Schematic cross-section view of different type of AlGaInP LEDs: (a) absorbing substrate (AS); (b) absorbing substrate (AS) with DBR; (c) transparent substrate (TS)



GaAsP and GaP:N LEDs, have much lower luminous efficiency. These LEDs are not suitable for high-brightness applications because of their inherently lower quantum efficiency. The GaAsP LEDs are mismatched to the GaAs substrate and therefore have a low internal efficiency. The GaP:N LEDs also have low efficiency because of the nitrogen-impurity-assisted nature of the radiative transition. However, AlGaInP LEDs have high luminous efficiency suited to the visible spectrum from the 570 nm (yellow) to 650 nm (orange). Hence, AlGaInP LEDs are an excellent choice for high luminous efficiency devices in the long-wavelength part of the visible spectrum. New record light-efficiency levels were achieved for this spectral regime, and as a consequence, new applications for LEDs are in the process of being developed.

2.2.2 Long Wavelength LED Technology: AlGaInP System

Today, the quaternary alloy AlGaInP material system is the primary material system used for high-brightness LEDs emitting in the long-wavelength part of the visible spectrum [4–6]. The AlGaInP epitaxial layer can be lattice matched to GaAs and is grown by MOCVD/MOVPE [7]. It has been introduced to yield substantial improvement in the performance in the red-orange and amber spectral regions and potentially in the green. Conventional AlGaInP LEDs are shown in Fig. 2.4a. Nevertheless, the portion of the light emitted from the active layer towards the substrate is completely absorbed by the GaAs absorbing substrate.

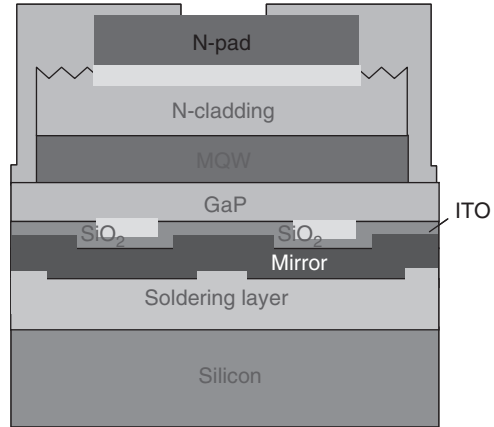
Therefore, the external quantum efficiency of this kind of conventional AlGaInP LED is small. The thermal conductivity of GaAs is only 44 W/m K. The low thermal conductivity of the GaAs substrate is not sufficient to dissipate the heat generated when the LED device is driven in high current.

The substrate absorption problem can be minimized by growing a distributed Bragg reflector (DBR) between the LED epitaxial layer and the absorbing GaAs substrate, as shown in Fig. 2.4b. However, the maximum reflectivity of the DBR layer used in AlGaInP LED is only about 80%, and its reflectivity also depends on the reflection angle. The DBR layer can only reflect the light near the normal incidence. For the oblique angles of radiated light, the DBR layer becomes transparent, and light will be absorbed by the GaAs substrate [8–11]. Hence, a more significant improvement in extraction efficiency is to replace GaAs with GaP transparent substrate through the wafer bonding process after epitaxial lattice matched growth. Thus, in Fig. 2.4c, this new class of AlGaInP LEDs called transparent-substrate (TS) LEDs is compared with the absorbing-substrate (AS) LED on GaAs-wafers. Figure 2.4 shows the comparison with the three types of AlGaInP LEDs.

Despite the improvements in extraction efficiency, the use of LEDs in high input power applications remains limited because of the low thermal conductivity of the substrate. To achieve higher light output performance, it is necessary to drive the LED at a higher current and to use a substrate with high thermal conductivity to efficiently dissipate heat from active layer. Many companies fabricated AlGaInP LEDs on Si-wafers using a metal combination of Au and AuBe for bonding. Despite the intermediate dielectric layer, the LEDs benefited from the good thermal properties of silicon, which has 3.2 times higher thermal conductivity than GaAs, thus providing a good heat dissipating ability. The increased thermal conductivity decreases joule heating and increases the quantum efficiency of the LEDs. Researchers successfully replaced GaAs with Cu substrate. This Cu-substrate-bonded LED device can be operated in a much higher injection forward current and high luminous intensity, several times higher than those used in traditional AS LEDs. The transparent conducting ITO and reflective layer between the epitaxial layer and the substrate to enhance the light extraction efficiency were also added. The luminous intensity of this design was 1.46 times greater than that of the conventional LED in the normal direction, and the output power (at 350 mA) increased by approximately 40% as compared with that of the conventional LED. Today, as the development of AlGaInP LEDs progresses, the most effective design to improve its external quantum heat dissipation ability is to combine the reflective structure with a high thermal conductive substrate through the metal bonding technique. However, because of the different CTEs and the intrinsic stress between different materials in the LED device structure, the crack problem may occur either during the removal etching process of the GaAs substrate or the annealing process after the GaAs removal.

The high-brightness LED structure was designed and fabricated by Epistar Corporation. The structural diagram of the LED is shown as Fig. 2.5. The multi-layer film-substrate structure, which includes a number of stacked films, such as an epitaxial layer of LED, SiO₂ isolation structure, ITO layer, silver (Ag) mirror layer, and eutectic bonding metal of gold/indium materials (AuIn₂), was in the range of

Fig. 2.5 The structural diagram of high-brightness AlGaInP LED



several micrometers to hundreds of angstrom. In addition, the GaAs substrate was replaced with a silicon substrate through the eutectic metal bonding technique. The detailed dimensions of each component will be introduced in the next chapter. The LED structures were grown on 3-in. GaAs wafers through low-pressure metalorganic chemical vapor deposition (MOCVD), with an average fabricated temperature of 750°C. The LED structure consisted of an n-GaAs buffer layer, n-InGaP etching stop layer, n-GaAs ohmic contact layer, AlInP n-cladding layer, undoped AlGaInP MQW active region, AlInP p-cladding layer, and a p-GaP window layer. The PECVD SiO₂ structure was fabricated at 200°C and patterned by an etching process. The ITO layer was placed on the AlGaInP LED to act as a current-spreading layer and was fabricated by an electron beam gun (E-Gun) evaporation system at 330°C. The Ag layer was deposited on the ITO layer to act as a mirror layer at 50°C. Then, the first bonding metals of Ti/Pt/Au/In were deposited at 80°C. The second bonding metals of Ti/Pt/Au were deposited on the host Si substrate [10], which served as a heat sink substrate. The thermal conductivity of the Si substrate was 124 W/m K, which is much higher than the value of GaAs base (44 W/m K).

2.2.3 Blue LED Technology: InGaN/GaN System

Starting early in the twentieth century, there were several reports of light emission from materials due to applied electric fields, and a phenomenon termed “electroluminescence” (EL). Due to that the materials properties were poorly controlled, and the emission processes were not well understood. For example, the first report in 1923 of blue EL was based on light emission from particles of SiC which had been manufactured as sandpaper grit, and which contained “unintentionally” p–n junctions. By the late 1960s, SiC had been extensively

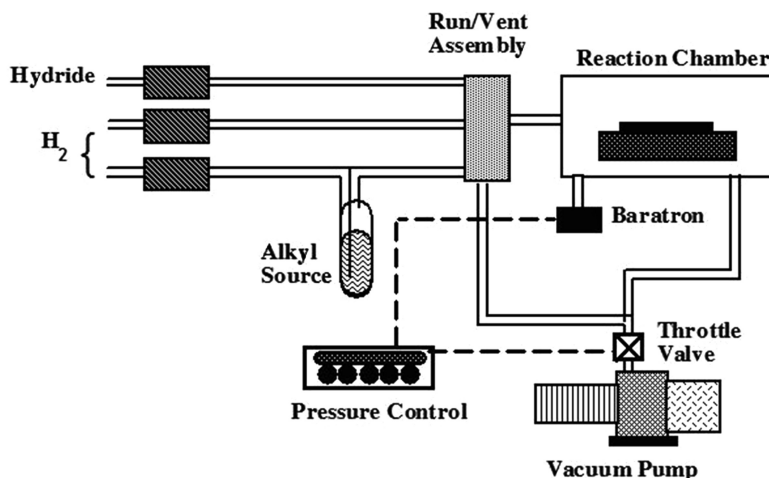


Fig. 2.6 Schematic diagram of MOCVD system

studied in order to enhance the efficiency. However, it was never more than about 0.005% due to SiC naturally being an indirect band gap material. The best efficiency of SiC LEDs till now is only 0.03% emitted at 470 nm.

The high brightness blue LED is actually implemented by InGaN/GaN material system. Studies of GaN material can be traced back into 1930s and 1940s. In the late 1960s, researchers attempt to grow GaN film from halide vapor phase epitaxy (HVPE) approach and obtained single GaN film on heterogeneous substrate (e.g., sapphire). However, all the GaN film grown at early 1960s were naturally n-type without intentionally doping, and it was a great challenge to implement p-type GaN film, because the lack of p–n junctions in Group III nitrides (and their poor crystal growth quality) stalls InGaN/GaN system research for many decades, until two major breakthroughs have been achieved:

- At 1989, Professor Isamu Akasaki shows a breakthrough on Mg-doped GaN sample to solve the p-type doping dilemma by electron-beam to annealing, and he demonstrated the true p–n conducting material [11, 12].
- At 1995, Professor Shuji Nakamura demonstrates the first high power blue LED with an efficiency exceeding 5% [14–16].

These two great achievements are widely credited with re-igniting the III–V nitride system. In the following paragraph, we are going to discuss the key aspects on the blue LED technology, including:

- Key LED chip manufacturing principles: Including MOCVD principle/equipment and buffer layer design.
- Key LED technology: Including the epitaxy process and chip forming technologies.

2.2.4 Epitaxy Growth: MOCVD Equipment

Combining the merit of the capability of volume production as well as adequately precise growth control, MOCVD system (as shown in Fig. 2.6) dominates almost all the field of commercial III–V compound epitaxy. MOCVE applies metal-organic compounds such as trimethyl gallium (TMGa) or trimethyl aluminum (TMAI) as precursors for the material in thin films. The precursors are transported via a carrier gas to a heated zone within a growth chamber. Thin films are produced when the precursors react or dissociate with another compound. The optical and electrical property of the resulting LED is directly related to the composition of the deposited materials and doping within the epilayers with specific elemental materials.

Theoretically, MOCVD is a nonequilibrium growth technique that relies on vapor transport of the precursors and subsequent reactions of Group III alkyls and Group V hydrides in a heated zone. The basic MOCVD reaction describing the GaN deposition process is:



However, the detail of the reaction is not fully understood, and the intermediate reactions are much complex. Further research is needed to understand the fundamentals of this crystal growth process.

Various researchers employ both atmospheric-pressure and low-pressure MOCVD reactors in the growth of GaN. In Japan, the majority utilizes atmospheric pressure reactors because of the high partial pressures of ammonia; on the contrary, the low-pressure system occupies an overwhelming portion in the other countries.

MOCVD reactor designs for GaN growth must overcome problems presented by high growth temperatures, pre-reactions, flows, and film nonuniformity. Typically, very high temperature level is required during the GaN growth, because of the high bond-strength of the N–H bond in ammonia precursors. Hence, the thermodynamic ammonia will be pre-reacted with Group III metalorganic compounds in order to form nonvolatile adducts. These contribute to the current challenges for researchers to design and scale-up of III–V nitride deposition systems. Much research activity is needed in the scale-up and understanding of the mechanism of gallium nitride growth by MOCVD.

2.2.5 Epitaxy Growth: Buffer Layer

Due to that there is no high-quality and low-cost GaN bulk single crystal, all technological development of GaN-based devices relies on heteroepitaxy. There are two main substrates commercially available for GaN film growth, 6H–SiC and sapphire. Because of intellectual property (IP) limitation (IP of growing-semiconductor-device-on-SiC is exclusive licensed to Cree by NCSU), most of LED chip companies adopt c-sapphire (0 0 0 1) as growing template.

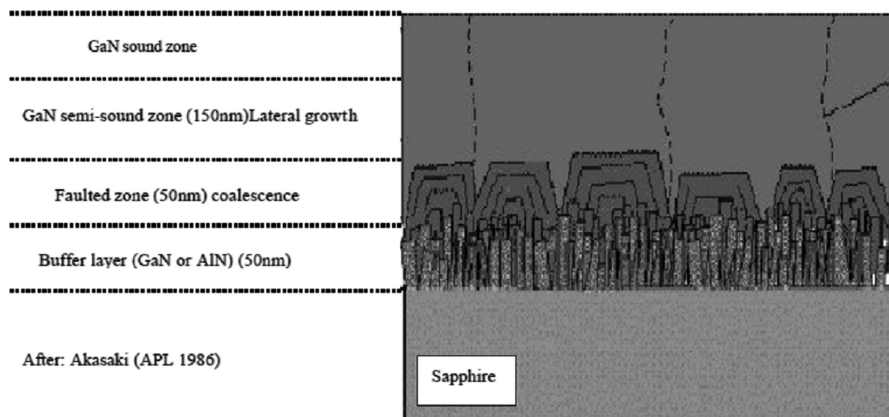


Fig. 2.7 The final structure of buffer layer

The crystallography of the c-sapphire surface is complex and can be terminated by different chemistries. Annealing this surface in flowing H_2 within the deposition system between 1,000 and 1,100°C is a commonly employed cleaning procedure to form a relatively stable Al-terminated surface prior to grow the buffer layer.

Due to that sapphire and GaN have different lattice constant, a special growth technique termed multistep pre-growth processes has been developed to overcome the lattice mismatch and to obtain better process quality. Multistep pre-growth processes involve either sapphire pretreatments or using buffer layers. Major process breakthroughs, e.g., two-step AlN treatment by Prof. Akasaki [13] and low temperature GaN (LT-GaN) by Prof. Nakamura (Fig. 2.7), has been achieved to provide a good nucleation surface and thus solved many problems in hetero-epitaxial MOCVD growth on sapphire.

In more detail on AlN buffer layer process: the sapphire is annealed under flowing NH_3 at temperature larger than 800°C. Nitrogen-containing species from the decomposed NH_3 react with Al atoms on the substrate to form a very thin AlN layer which lowers the lattice mismatch with subsequently grown III-nitride films relative to that with sapphire and modifies the surface energy of the substrate.

Nakamura adopted the same idea but not AlN. By atmospheric-pressure MOCVD, he obtained the same beneficial effects of an AlN buffer layer by using GaN low-temperature layer, which starts with a low temperature thin GaN deposition, followed by a high temperature growth to complete the GaN buffer.

2.2.6 Start-of-the-Art of Blue LED Process (1): Epitaxy

Before growing the LED structure, normally 2–6 μm undoped GaN (u-GaN) are deposited, prior to n-type GaN at the temperature around 1,000°C. The purpose of

u-GaN is mainly to reduce the threading dislocation propagating from buffer layer in favor of bettering the quality of LED structure.

On top of the u-GaN, we grow n-type GaN, active layer, and p-type GaN, respectively:

- n-type GaN: Doping silicon is the most popular way to form n-type GaN. Moreover, most process will grow a pre-strain layer before active layer to pre-compensate the strain between n-type GaN and active layer. The growing temperature of n-type GaN is typically equal or slightly higher than that of u-GaN.
- Active layer: The choice for active layer used to be double heterojunction (DH) structure. Because of improvement of efficiency, precise wavelength control and narrower full width at half maximum (FWHM) in wavelength, multi-quantum well (MQW) structure seems to be a widely acceptable choice over the world. The growing temperature of InGaN/GaN MQW must be lower enough in order to successfully introduce indium into the film to emit the desired wavelength.
- p-Type GaN: A long-standing problem was the failure to achieve p-type doping in GaN materials. So far, magnesium is only dopant that is capable of producing p-type GaN. Before 1993, it was very difficult to obtain p-type GaN. Prof. Akasaki showed that a solution existed: He discovered that the low-level electron beam irradiation in an electron microscope could form p-type GaN. However, it was Nakamura who fully solved the problem of p-type doping: He found that all previous GaN researchers had annealed their samples in ammonia (NH_3). Ammonia dissociates above $\sim 500^\circ\text{C}$, releasing atomic hydrogen, which passivates the acceptors. Therefore, Nakamura switched to annealing in a clean nitrogen (N_2) atmosphere and thereby invented a reliable method to achieve high-quality p-type GaN materials.

Due to a lattice mismatch between the InGaN well layer and the GaN barrier layer of MQWs, a polarization field in the active region, causes inadequate confinement of electrons in the active region, which causes electron overflow to the p-type region and results in an efficiency droop. Growing the electron blocking layer (EBL) between p-type and MQWs is a proven method to improve the efficiency of LEDs, by effectively confining electrons in the MQW region.

The following chart in Fig. 2.8 is the typical flow of LED epitaxy process.

2.2.7 Start-of-the-Art of Blue LED Process (2): Chip Forming

After GaN epitaxy, the following GaN LED process is relatively straightforward, including frontend (mesa forming, TCL, Pad forming, and passivation) and backend (grinding, dicing, and binning) chip forming process:

- Frontend process:
 - Mesa forming: Because sapphire substrate is nonconductive, we have to define the mesa area in order to expose n-type GaN.

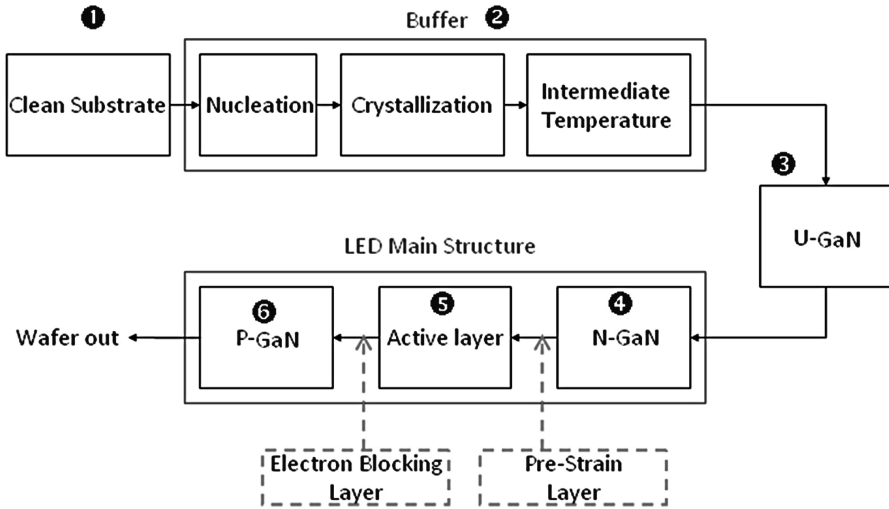


Fig. 2.8 Major epitaxy process flow of blue LED

- **Transparent conductive layer (TCL) forming:** Normally indium-tin-oxide (ITO) is deposited onto p-type GaN by E-gun or sputtering. Since the hole mobility of p-type GaN nowadays is still a issue, as a result, the use of TCL is to improve the current spreading [17] and thus electroluminescence.
 - **Pad forming:** For providing the current path, properly-chosen metals are deposited onto p- and n-type GaN as p- and n-Pad. The selection rule for metals is that it has to make p- and n-contact be ohmic, to be oxidize free and to be able to well bond with the external connecting wires.
 - **Passivation:** For better reliability, passivation, such as SiO_2 or SiN_x , are deposited to prevent LED from the moisture.
- The frontend process is the illustration of the paragraph above as Fig. 2.9.
- **Backend process:** The main purpose of the back end of the line (BEOL) is to separate LED chips into individual ones.
 - **Grinding:** The original sapphire substrate is too thick to scribe; therefore, we have ground the wafer first.
 - **Dicing:** Scribe-and-break is a prevalent method for individualizing the burgeoning GaN LEDs by virtue of high throughput, low cost, ease of use, process tolerance, and high yields. The wafer is experiencing melting and ablation so as to create thermal crack that is precursor to the following breaking process. Commercially, it is either front-scribe-and-back-break or back-scribe-and-front-break, depending on the process design.
 - **Binning and sorting:** Statistically, most of the process variations behave the normal distribution, so do the final products. In order to make good-quality commitment to the customers, it is imperative to separate bad ones from good

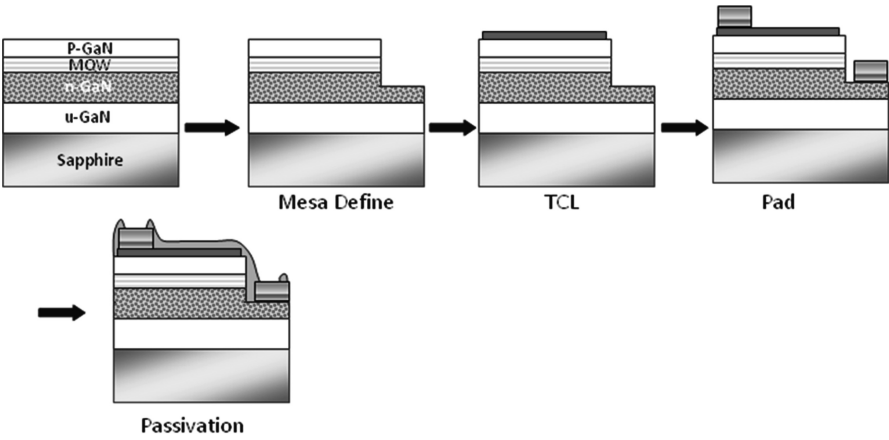


Fig. 2.9 Schematic diagram of blue LED chip process

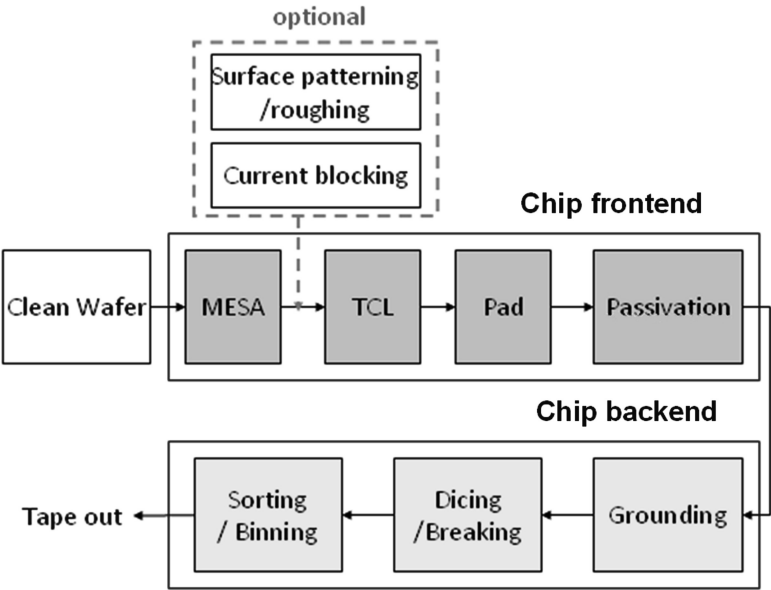


Fig. 2.10 The typical flow of complete LED chip process

ones! And, why binning? It is not only for us to make corresponding price by the grade of the products, but also it is easier for customers to use due to the small variation of the-same-bin product.

The total frontend/backend process is summarized in Fig. 2.10.

2.3 Level 1: LED Packaging

2.3.1 Overview

LED packaging is responsible for the electrical connection, mechanical protection/integrity and heat dissipation of LED chip. Depend upon the LED chip specification and application field, the design concept/structure of the LED packaging varies. In the following paragraph, the concept of the conventional LED packaging, high-brightness LED packaging, and wafer-level chip integration technology will be described.

2.3.2 Conventional LED Packaging

A conventional LED package includes electrical lead, wire, die attach and encapsulant. The most divergence of LED package and IC package is should consider the light extraction from LED package. The LED chip is surrounded by transparent encapsulant and electrical connection via the wire. The LED chip in the conventional package is operating beyond 120 mA (or called low-power chip) and usually using the surface mount technology. There are many types in conventional packing and mostly known as “5 mm lamp” or “SMD5630” as shown in Fig. 2.11. In convention package, it has two different surface shapes, one is hemisphere and the other is planar-surface. The light through the hemisphere is like the Lambertian surface and planar-surface has wider far field angle than hemisphere shape. It has

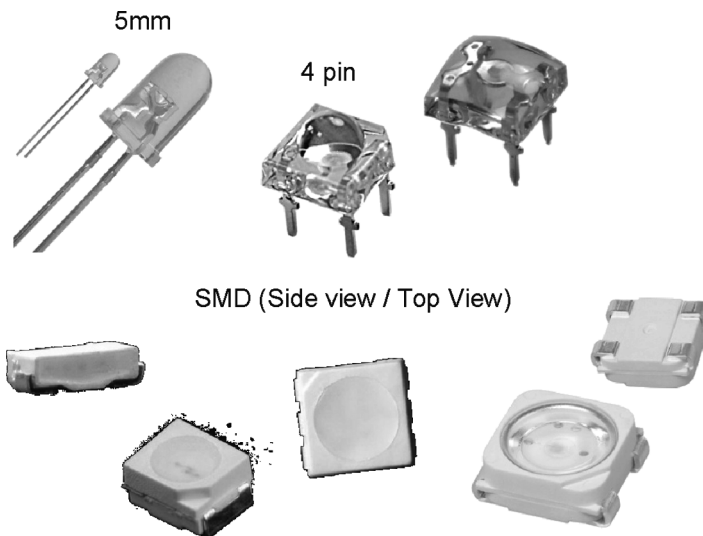


Fig. 2.11 The different types of LED package

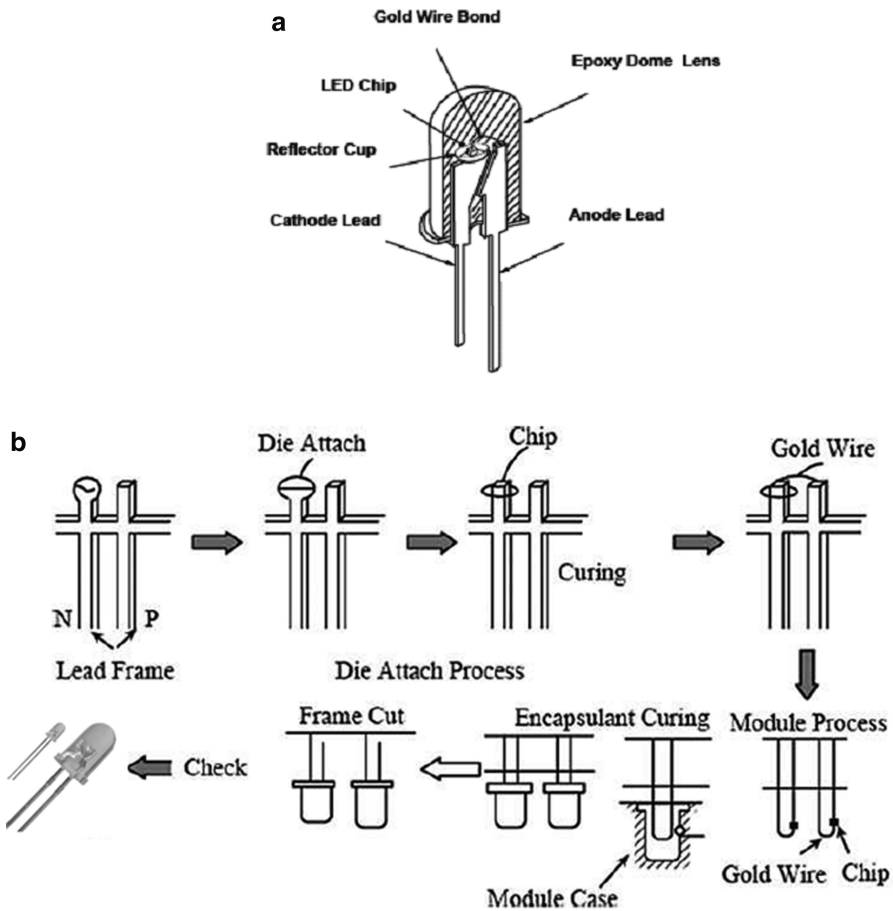


Fig. 2.12 The (a) structure and (b) packaging process flow of conventional LED packaging

highly reflective metal (like silver) deposit on the contact surface which between chip bottom surface and package top surface. Functions of encapsulant are not only providing protection against humidity and chemicals damage but play the role of a lens in the package.

The process of the conventional LED packaging includes die bonding, interconnect forming, encapsulation/phosphor curing and frame cutting, as illustrated in Fig. 2.12. A pre-reformed leadframe, which comprised of multiple N/P legs are provided, and the LED chip are mounted on to one leg. Interconnect, e.g., gold wire and aluminum wire is applied to connect chip to two legs. Following, the leadframe are sent to the encapsulation process to form the dome shape transparent protection polymer.

These low-power LEDs are widely used in the application of indicators, signals, backlighting, with the price in the range of 0.1–0.2 \$/part.

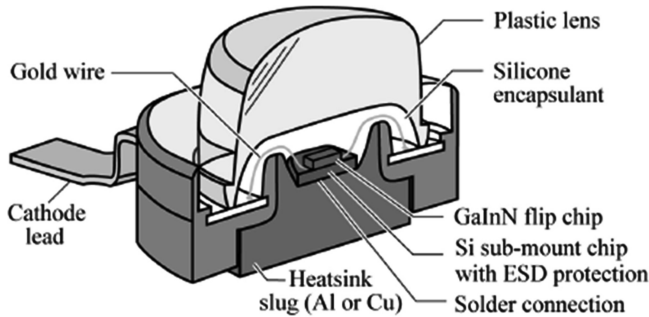


Fig. 2.13 Schematic diagram of high power LED packaging

2.3.3 High Brightness LED Packaging

High brightness LED (HB-LED) packaging, or called high power LED packaging, use operation current of more than 350 mA and generate more than 130 lu/W light output. High current/power usually induces higher temperature at the LED chip, and the LED light efficiency will dramatically decrease when the LED temperature increase. Hence, the thermal dissipation is much severer than the conventional LED packaging, where new packaging concept is needed.

HB-LED packaging will apply advanced thermal management solution for heat dissipation. Refer to Fig. 2.13 as an example, the chip is first mounted on Si-based submount and large heat sink (slug), and connected to one side of the die with an Au/Al wire bond. The other can be connected to the lead with another wire bond, or directly through the bottom of the die through the die attachment. After wire bonding interconnection, the chip is encapsulated with silicone. In a white LED, the phosphor material is suspended in the silicon. Finally, the entire component is molded into an epoxy casing that provides directionality to the light and further protection to the die and leads.

The process flow of HB-LED can be shown in Fig. 2.14.

- Dicing: A two-steps dicing technology is widely used in the LED packaging manufacturing, including:
 - The GaN scribing step must be carried out with high precision. To have good performance, the diodes must have very straight and smooth edges. This step can be done by laser or diamond techniques.
 - The cutting of the substrate requires less precision and aims to separate the diodes. Diamond saws as well as scribe (by diamond or laser) and break techniques are normally used.
- Die bonding
 - Good precision of the die bonding will ensure the optical center of the LED packaging.

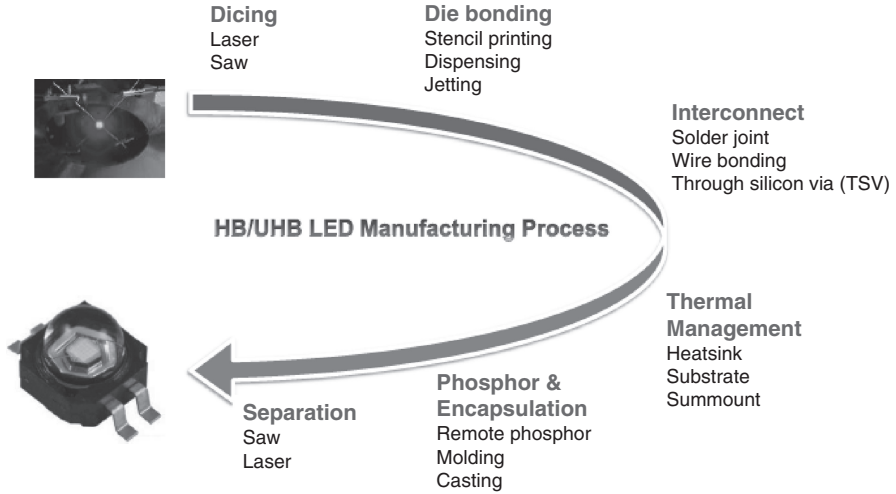


Fig. 2.14 Packaging process flow of HB-LED packaging

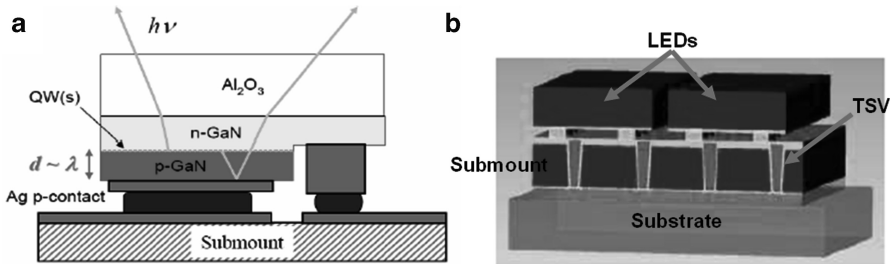


Fig. 2.15 Advanced interconnect technology for HB-LED: (a) flip chip and (b) TSV

- Good uniformity of die bonding process determines the thermal performance of the HB-LED packaging.
- Currently, conductive polymer and solder paste is widely used.
- Interconnect: The HB-LED interconnect is subject to high current, and the reliable interconnect technology is required.
 - Wire bonding: Traditional Au/Al wire bonding technology is also applied for HB-LED, with the guarantee of high/stable current flow. New wire bonding technology, such as ribbon wire bonding, is developing.
 - Flip chip: As illustrated in Fig. 2.15a, the LED based on the transparent sapphire can be flip-chipped [18] by the solder-based interconnect.
 - Through silicon via (TSV): Forming the TSV in the silicon submount, and mount the LED chip onto it. High thermal conductivity of silicon material (submount) is expected to improve the packaging thermal performance, as illustrated in Fig. 2.15b.

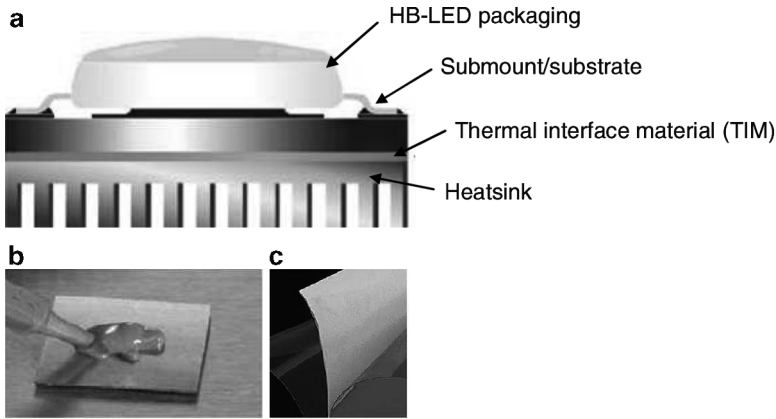


Fig. 2.16 Thermal interface material: (a) illustration of the TIM, (b) thermal grease, and (c) thermal film

- Thermal management: There are several aspects to further improve the thermal performance of HB-LED packaging:
 - Submount and substrate: Thermal substrate materials (e.g., metal core PCB) provide primary heat spreading, heat transfer to the heat sink, electrical connection to the driver, and mechanical mounting. Thermal enhanced materials, such as metal core PCB (MCPCB), ceramic substrate, and TSV for thermal dissipation, are used.
 - Thermal interface material (TIM): Thermal interface materials (e.g., film or thermal grease) improve heat dissipation and electrical isolation [19], as illustrated in Fig. 2.16b.
 - Heat sink: Heat sinks dissipate heat to the ambient environment.
- Phosphor, encapsulation and lens
 - Phosphor is widely used for the white lighting generation from blue LED. YAG:Ce²⁺ and YAG:Eu²⁺ are the mostly used material.
 - Silicon-based encapsulation and lens are widely applied, due to high thermal resistance, photo-thermal stability, less degradation.

2.3.4 Wafer-Level Chip Integration (WLCI) Technology

In contrast with conventional wire bonding packaging, a new wafer-level process has been developed so that it is able to electrically connect each chip without applying wire bonding. Borrowing the concept from IC/package industry [10, 20–21], a process called “Wafer Level Chip Integration (WLCI)” technology has been developed to construct hybrid integration of various chips on a substrate.

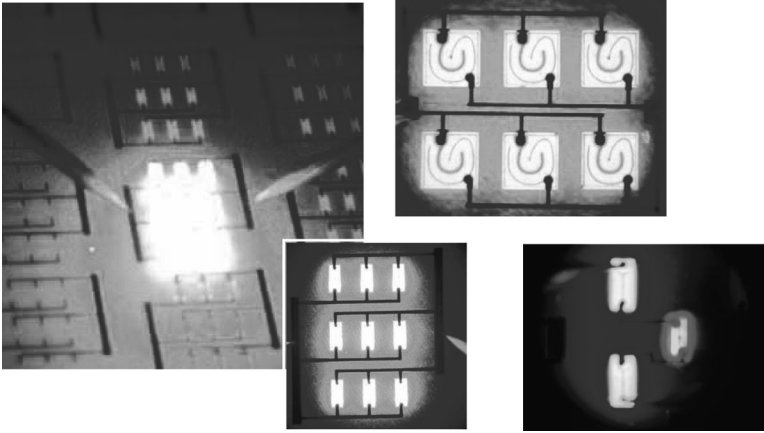


Fig. 2.17 Picture of various multiple chip integration by WLCI technology (Epistar provide)

The chip process of WLCI technology is based on the normal LED chip process with three extra steps:

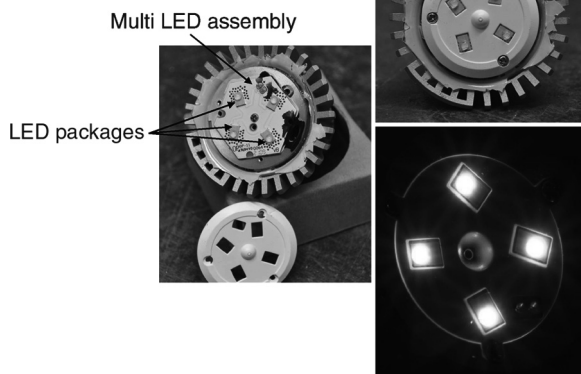
- (a) The LED chips are placed on a substrate. There is not much restriction on the arrangement rule except for the placement accuracy. The accuracy is to be controlled to a degree of $15\ \mu\text{m}$ or less to improve the process yield. Chips used in this platform can be a combination of electronics and optics chips with variety of functions.
- (b) The empty space between LED chips is filled with filling material to provide a smooth surface for the following metal interconnection. The filling material is supposed to be transparent in the range of emission spectrum of the designated LED chips for not reducing the light output.
- (c) The predetermined electrical connections between chips are through photolithography and thin-film deposition instead of wires. With this technology, it becomes possible to do heterogeneous chip interconnection in wafer form.

Figure 2.17 shows three examples of combining multiple chips to achieve different application by WLCI technology.

2.4 Level 2: Multi-LED Assemblies

The LED packages has a relatively small dimension (roughly $4 \times 5\text{mm}^2$ to $10 \times 10\text{mm}^2$), which shows a gap towards the lighting application, such as retrofit bulb and luminaire. A transfer layer, multi-LED assemblies, is presented to fulfill such gap and enhance the thermal performance of SSL application (Fig. 2.18). In this section, mechanical consideration of the multi-LED assemblies and the white light generation will be described.

Fig. 2.18 Multi-LED assembly in the retrofit application (Source: Philips)



2.4.1 Mechanical Considerations

The LED packages are assembled onto the large PCB by the solder or epoxy glue/adhesive. The bonding process can be achieved by the solder reflow or epoxy curing.

However, these bonding processes cause severe luminaire reliability risk. Take solder bonding as an example, the LED packages can stand the lead-free solder SnAgCu melting temperature of roughly 220°C . But in reality, the maximum reflow temperature of $40\text{--}50^{\circ}\text{C}$ above the melting temperature. High reflow temperature will induce the LED packaging epoxy degradation and/or delamination initialization/propagation. On the other hand, due to the high coefficient of thermal expansion (CTE) mismatch between the PCB and LED packages, the reliability of such solder/adhesive will dominate the overall luminaire reliability.

In order to reduce costs for LEDs, a logical step is to integrate multi-LEDs onto PCB directly, and skip the LED package level as much as possible. Then different processing steps can be omitted and less (expensive) material will be used. Using multiple LED dies per product will increase the lumen output per product. However, it will pose other challenges to the system. The two most important ones are (1) proper thermal management to get rid of all the heat and (2) directing/shaping the light spot (Fig. 2.19).

2.4.2 White Light LED

Challenges of white light emitting by LED technology are presented, because only a particular wave length of light can be generated by single LED. To emit white light with acceptable CRI, the LED manufacturer commonly uses three approaches: wavelength conversion, color mixing, and homoepitaxial ZnSe:

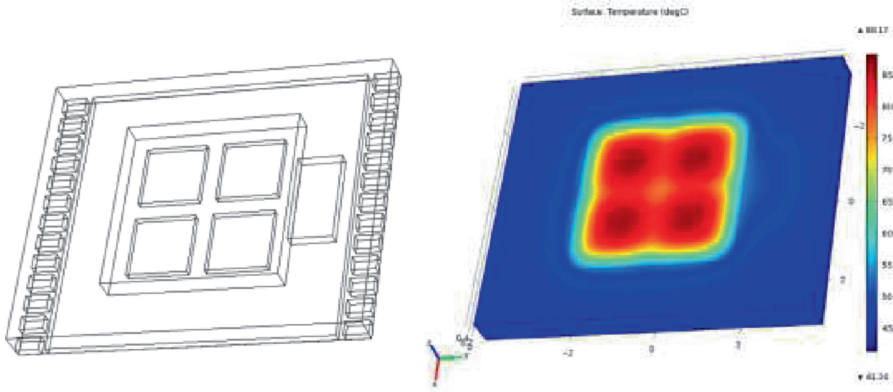


Fig. 2.19 Concept of a four die LED with integrated driver package (*left*), and thermal simulation result (*right*)

1. Wavelength conversion: It involves converting all or a part of LED's emission into visible wavelengths that are perceived as white light:
 - (a) Blue LED and YAG-based phosphor: The YAG-based phosphor is excited by the blue LED, and results in the appearance of white light. This method is most widely applied in the SSL industry, due to the most efficient and low cost. However, the material of yellow phosphor usually contains of rare earth, and the material scarcity concern maintains and substitution possibility is exploring.
 - (b) Ultraviolet LED with RGB phosphor: Similar to previous application, the light from ultraviolet LED is completely converted by the RGB phosphor.
 - (c) Blue LED and quantum dots (QDs): Quantum dots (QDs) are extremely small semiconductors crystals (between 2 and 10 nm). These quantum dots are 33 or 34 pairs of cadmium or selenium on top of the LED. Hence the quantum dots are excited by the LED and generated the white light. The excited wavelength from the QDs depends upon the particle size [22, 23].
 - (d) Color mixing: Another method is to mix fundamental light sources and generate the white light. Color mixing can be implemented by two LEDs (blue and yellow), three LEDs (blue, green, and red), or four LEDs (red, blue, green, and yellow). Because of no phosphor, there is no loss of energy during the conversion process; as a result, color mixing is more efficient than wavelength conversion.
2. Homoepitaxial ZnSe: The blue LED is placed on to a homoepitaxial ZnSe, and the blue light is generated by the blue LED and yellow light from the ZnSe substrate. From the literature [24], this technology can generate white light with color temperature of 3,400 K and CRI of 68 (Fig. 2.20).

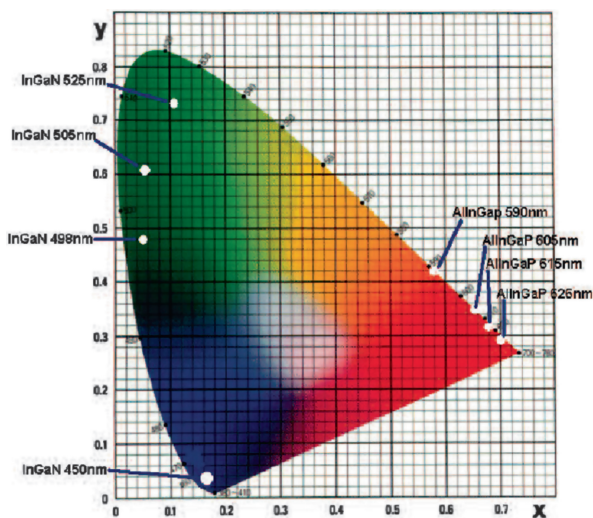


Figure 5. Chromaticity coordinates of typical single-wavelength LEDs shown on a standard CIE chromaticity diagram [adapted from Schubert and Miller, 1999].

Fig. 2.20 Color mixing for white LED

2.5 Level 3: LED Modules

LED requires constant current with DC power. The SSL electronic driver is used for converting AC power into DC, or from one DC level into higher/lower DC. These LED electronics are expected to maintain the constant current and control of LED, performing several of electrical protection to LED, such as overvoltage, overload, and over-temperature shutdown. On top of the level 2: multi-LED assemblies, the electronics of SSL is presented and integrated.

Conventional SSL devices include three major parts: optical part, LED electrical driver, and interconnections between the latter two parts (Fig. 2.21). In each SSL system all these three parts exists, and they are necessary to make the system functional, however, with respect to the application they can be simpler or more complex. The electrical driver of SSL system prepares the required power for driving optical part. The primary and fundamental task of the SSL driver is to provide electrical power requirements for optical part of the system. There are lots of other functionalities can be defined and implemented in SSL driver. Dimming and color-changing capabilities are two examples of SSL system extra functionalities which already can be found in commercial products. Various driver architecture is applied for different applications, such as Buck (for output voltage is smaller than input one), Boost (for output voltage is smaller than input one), fly-back, and transformer-isolated converters (for main to LED lamp application).

Smart SSL—able to sense, describe the environment, and help to decide—will contribute to more than 70% of lighting energy saving. However, less components/

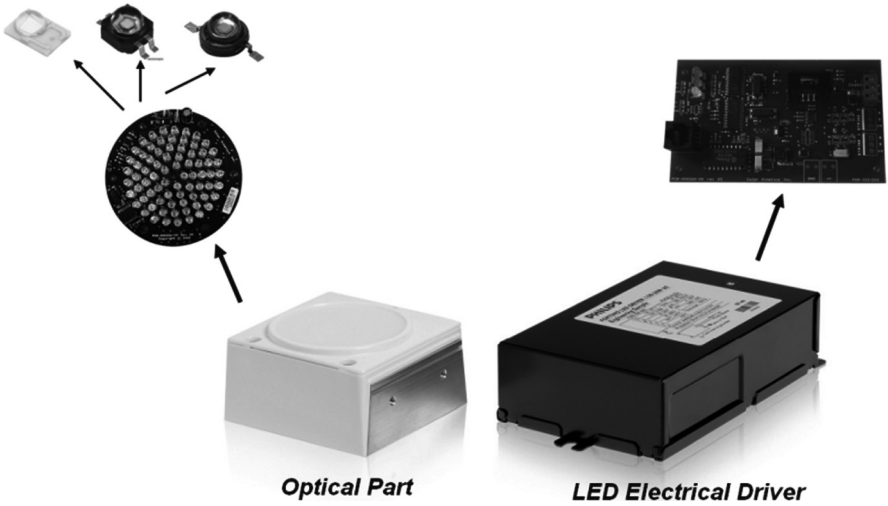


Fig. 2.21 Different parts of a general SSL system. Optical part is the light source of the system and includes LEDs. LED electrical driver (SSL driver) is the interface of the SSL optical part and the input power of the system. SSL driver also can be more than just a power converter and includes the controller and memory. These two parts of the system are interconnected to each other (Source: Philips Lighting)

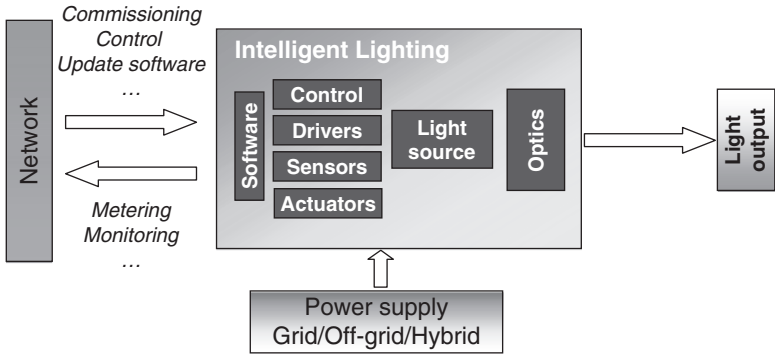


Fig. 2.22 Illustration of intelligent lighting architecture

systems integration results in a high price, large size, and less market acceptance of SSL products and in a nonoptimal energy-saving solution. As SSL is digital in nature, it has inherited excellent advantages to combine the lighting function with other functions (sensing, communication, control, etc.) to create smart and multi-function systems. Figure 2.22 shows the architecture of future SSL concept, where the controller/driver, sensor, communication units are presented.

2.6 Level 4: Luminaires

As the development of the SSL technology, two types of luminaires are developed to accelerate the market acceptance:

1. Retrofit bulb/lamps

Following the conventional usage of the light bulb, SSL industries create the LED base light bulb to replace the conventional incandescent and fluorescent light bulbs to enhance the market penetration of the LED technology. Figure 2.23 shows an example of retrofit bulb, which has the same fixture design as conventional light bulb and customers can direct replace their bulb without changing the fixture or the luminaire.

2. Beyond retrofit

The lifetime of the LED chip is expected to be more than 50,000 h, which is close to the luminaire. Further cost reduction concepts of directly integrating the LEDs into luminaires are presented by the beyond retrofit luminaires. Figure 2.24 shows a low-cost consumer luminaire, where the LED and driver electronics are integrated.

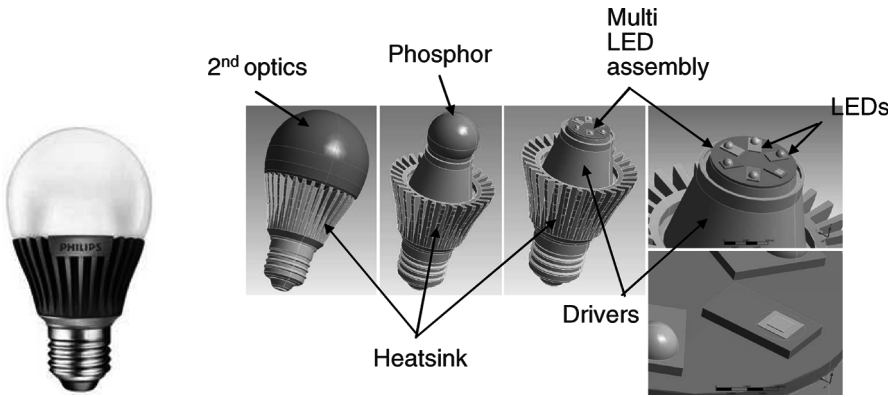


Fig. 2.23 An example of retrofit bulb (Source: Philips and European CSSL project)

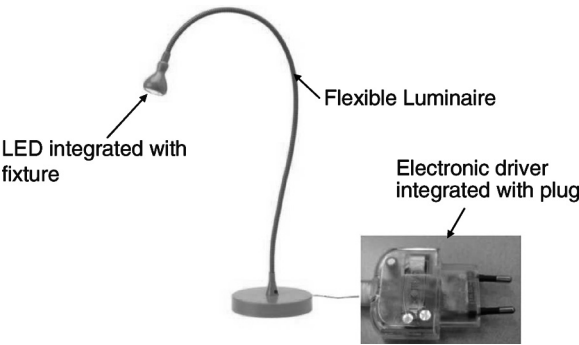


Fig. 2.24 Beyond retrofit: SSL consumer luminaire (Source: IKEA)

Fig. 2.25 Schematic diagram of thermal path of LEDs

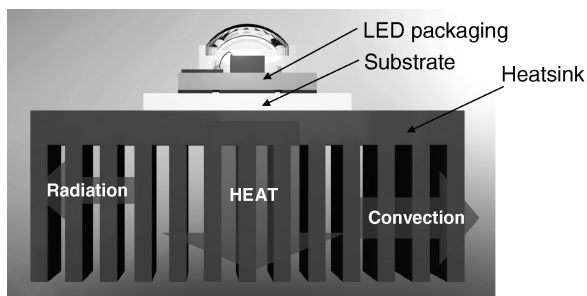
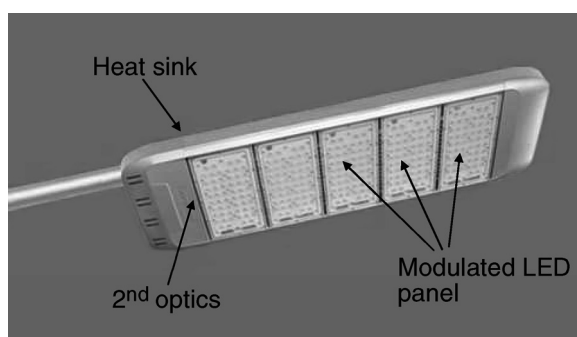


Fig. 2.26 Beyond retrofit: Street light (Source: Lampearl)

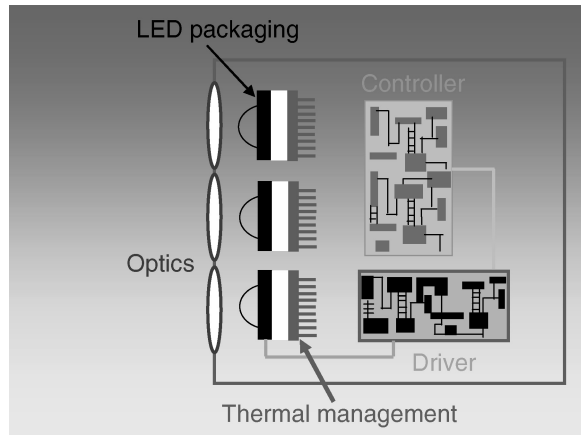


High power LED now is used from 500 mW to as much as 10 W in a single package and it is expected to apply even more power in the future. The chip heat fluxes are expected to be in excess of 70 W/cm^2 by the end of this decade, and about 100 W/cm^2 by 2018 [25], which has very high intensity of power. The application of conventional thermal packaging technology results in poor thermal performance to such chip designed LEDs with high temperature hot spot. Advanced thermal materials and novel thermal solutions which are already successfully applied on microelectronic packages have high potential to be used on LED module (Fig. 2.25).

The thermal management is one of the design key issues of luminaire, especially for the high power SSL application. Figure 2.26 shows an example of LED-based street lighting, where the heat sink is located at the opposite side of LED, and the heat sink covers almost all illumination area [26].

The design of the SSL luminaire is alike a designing of the mini compact system. Figure 2.27 demonstrated a luminaire design, where the key functional elements, such as LED, thermal management, optics, controller and driver. As increasing the SSL functionalities, the design challenge of the SSL luminaire is expected.

Fig. 2.27 Functional architecture of SSL luminaire



2.7 Level 5: Lighting Systems

Lighting systems is a complex system, which is a system composed of interconnected parts that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts. Lighting system comprises of multiple luminaires and/or types of luminaire, smart sensors, communication, control scheme, and data mining and data management. Examples, such as street lighting, building lighting, city lighting, are given (Fig. 2.28).

Various challenges of complex lighting system are foreseen:

- (a) The interactions: Between different disciplines (software, electronics, optics, mechanics, and thermal) and component/subsystem (sensors, communication, ventilation, heating, and air-conditioner).
- (b) Long lifetime: Lighting system is expected to be much longer than the components. A building is expected to be 50 years and a bridge is about more than 100 year. The corresponding lighting system will be expected to be functional as long as the objects stand. However, the advanced lighting system should be able to adapt by itself for the different user requirement and component/subsystem replacement.
- (c) Complex supplier ownership: Due to the size of the large system, it will be too difficult for a single supplier to cover all components. Hence, it is a scientific/engineering challenge to communication with each supplier at different levels, where a feasible standard is required.
- (d) Easy to maintenance.

In summary, a sustainable lighting system lifecycle is proposed in Fig. 2.29.



Fig. 2.28 SSL lighting systems: (a) Netherlands Pavilion at 2010 Shanghai world expo, (b) Guangdong Olympic Sports Center (Source: Lampearl)

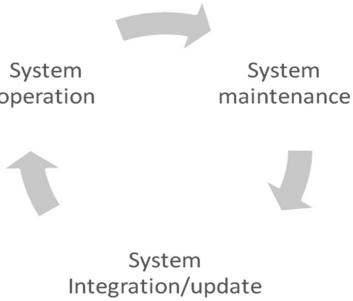


Fig. 2.29 Sustainable lighting system

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