1

A Brief History of Artificial Light and LED Packaging

1.1 Evolution in Artificial Light

Light is one of the most important ingredients for the survival of all living things. The primates as far back as two million years ago might have used fire from burning wood as artificial light [1]. This highly intelligent primates' survival instinct mastered the usage of burning wood for many other uses than to see and to be seen. The primates in the early years have also learned to make artificial light by making fire by rapidly grinding two combustible materials.

Light has fascinated human beings since the dawn of civilization, and artificial light has played an important role in human civilization. In the 1980s, archeologists unearthed an oil lamp made of stone in a cave in Southern France. The occupant of this cave was using the lamp for cave drawing [2]. This may be the first known lighting tool that uses fat-burning fuel. Carbon dating indicated the lamp might have existed some 38,000 years ago. These lamps were made from limestone or sandstone and can be easily fashioned with shallow depressions to retain the melted fuel. Chemical analysis of residues of the fuel has shown that it was probably animal fat [3]. This Paleolithic lamp, as illustrated in Figure 1.1, has the lighting power of a candle. Oil lamps are still in use today in some parts of the world, where electricity is not readily available or affordable [4]. Civilization has accelerated ever since the invention of artificial light, as their productive hours have extended beyond daylight into the night and even indoor activities [5]. The artificial light based on fuel-burning technology has since evolved from oil to kerosene and gas-discharged lamps [4].

In the nineteenth century, there was a breakthrough in artificial light when electric light was invented. Electric light or the incandescent light bulb was further perfected by Thomas Alva Edison [6]. However, this light source was very inefficient as it converted less than 5% of the energy to light and the rest was turned into thermal energy. In the early twentieth century, fluorescent and sodium lights took over the standard incandescent light bulb. However, this light source has its issues such as the content of hazardous materials like mercury and short product life span [4]. Hence, this allows the light-emitting diode (LED) to shine as it offers an alternative way of light generation. LED's spontaneous light emission due to radiative recombination

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Luruthudass Annaniah, Mohamed Salleh M. Saheed, and Rajan Jose.

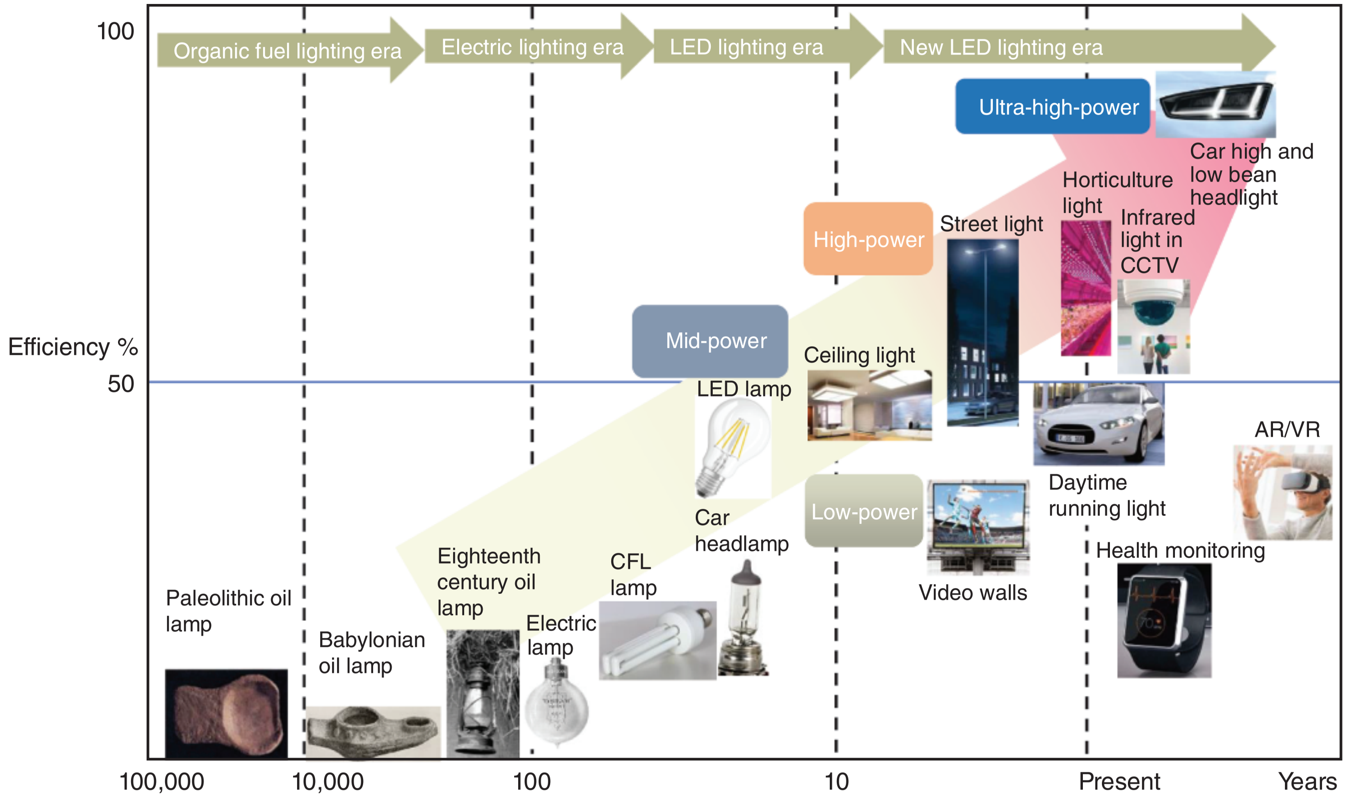


Figure 1.1 Evolution of artificial light.

of excess electrons and holes is an important selling point that attracts a lot of interest besides their energy efficiency.

Even though LED was discovered earlier than compact fluorescent light, it did not flourish as there was not much development or innovation in the early years. LED was first discovered by Henry Joseph Round in 1907. He found Silicon Carbide (SiC) illuminates when it is biased with 10 to 110 V. This early form of LED was very dim. In 1928, Oleg Vladimirovich Losev, a brilliant inventor and genius physicist, reported a detailed investigation of the luminescence phenomenon observed with SiC metal–semiconductor rectifiers. He found the light could be switched "on" and "off" rapidly, making it suitable for what he called "light relays." His discovery of crystaldyne, which was the first crystal amplifier and oscillator, and the invention of the first semiconductor LED generating visible light could be the basis for the development of semiconductor electronics. However, this SiC had an efficiency of only 0.03% and was not comparable to the current III–IV material system. In the late 1950s, Welker's [7] proposal suggested that compound semiconductors from III and V groups of the periodic table should have comparable semiconductor properties to those of germanium (Ge) and silicon (Si). These led to the discovery of infrared (IR) emission from gallium arsenide (GaAs) crystals with very low quantum efficiencies of around 0.01–0.1%. This early observation and understanding of band structures of semiconductor materials were soon followed by the quest for visible LED. This is where Nick Holonyak and Bevacqua invented the red LED in 1962 [8, 9]. They were using vapor-phase epitaxy (VPE) of gallium arsenide phosphate (GaAsP) on a GaAs substrate. This technique was used to produce the first red luminescence diode, triggering an industrial production revolution in LED manufacturing, where many applications like indicator lights and alphanumeric displays benefited [7]. Monsanto Corporation was the first to start commercial mass production of LED in 1968. It produced low-cost GaAsP LEDs. Hewlett–Packard (HP) Corporation joined the race to develop LEDs in the late 1960s, followed by other corporations [10]. Development of new semiconductor materials has made it possible to produce LEDs in a variety of colors as they become even more effective for use. However, high-brightness and efficient blue LEDs based on gallium nitrate (GaN) came in the early 1990s. Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura made it possible to obtain very efficient blue and green LEDs [11]. This led them to win the Nobel Prize for Physics in 2014. The invention of efficient blue LEDs has enabled white-light illumination. In 1997, white light was demonstrated for the first time by combining a blue GaN LED with a yellow-emitting phosphor [12], which revolutionized solid-state lighting (SSL).

Figure 1.2 shows commercialized and widely used SSLs such as traffic signals, backlighting for screens, televisions, video walls, interior and exterior lighting for automobiles, home lighting, stage lighting, mobile phones, and many more applications. With continuous improvement in the performance and cost reduction in the last decades, SSL is replacing conventional light rapidly.

In comparison to conventional lighting, SSL has two highly desirable features: (i) energy-efficient and consequent reduction of carbon footprint and (ii) extremely versatile with many controllable properties, including the emission spectrum,

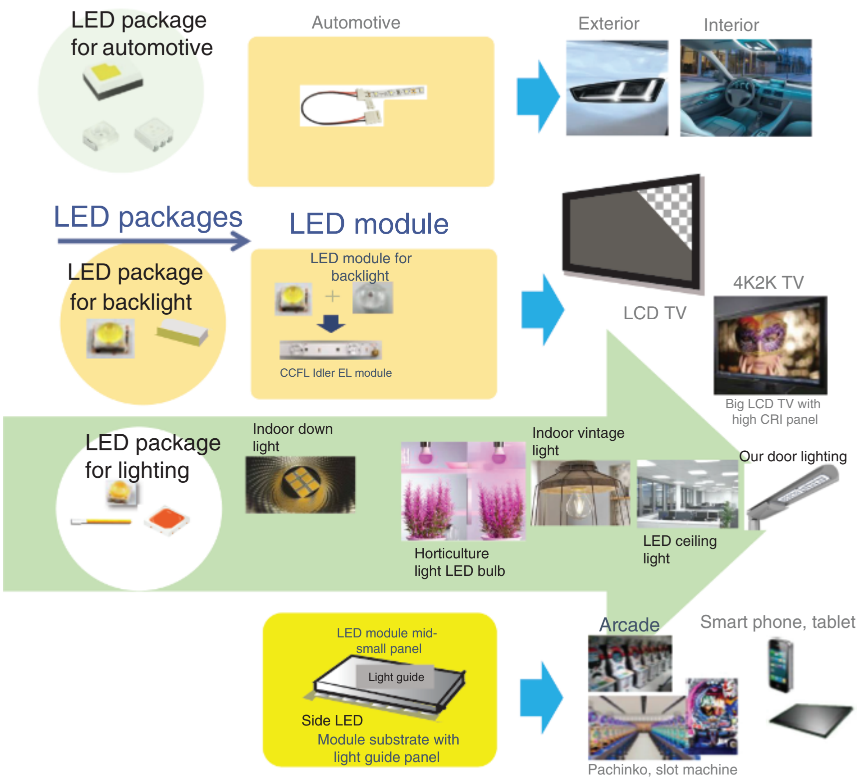


Figure 1.2 Solid-state lighting expanding application. Source: Courtesy of ams OSRAM GmbH.

direction, color temperature, modulation, and polarization. The impact of LEDs on the economy, environment, and quality of life has become very significant.

1.2 Impact of Light-Emitting Diode on the World

The invention of the GaN-based blue LED has significantly transformed the lighting industry. In the last decade, LED light sources have gone from being just an interesting novelty to a new light source option that can be used for energy savings, longer lifespan, and higher performance in almost any application. For example, a 15-W LED lamp can replace a 75-W incandescent lamp, deliver a useful lifetime averaging 25,000 hours, have adjustable lighting, require no warm-up time, and offer superb color rendering [13, 14].

LED provides significant energy savings because it converts energy efficiently compared to other light sources. The cost-saving advantages are revealed in a study by Ehrentraut and Meissner in 2010 on the impact of the conversion to SSL on US electrical energy consumption, as illustrated in Table 1.1. In this study, the energy consumption estimated by assuming the power consumption of solid-state light to produce almost identical light output is just a fraction compared to a 60-W

Table 1.1 Potential impact of conversion to solid-state lighting on U.S. electrical energy consumption.

General illumination lighting			
Performance estimates	**SSL product**	**60-W incandescent light bulb**	**23-W compact fluorescent lamp**
Light output (lm)	1000	1000	1200
Power (W)	6.67	60	23
Lumens/W (system)	150	16.7	52
Annual energy consumption (8 h/d, 365 d) (kWh)	19.5	175.2	67.2
Factor higher than LED	1	9	3.4
Annual energy cost per lamp (9.3 ¢/kWh)	US$ 1.81	US$ 16.29	US$ 6.25
Estimated annual energy savings with LED lighting: 2020 estimated baseline energy consumption for lighting: 7.5 quads			
% US lighting conversion to SSL	**Quads saved**	**$ saved (billions)**	
1%	0.05	0.33	Assumption: equal replacement of incandescent and fluorescent lighting
10%	0.49	3.23	
25%	1.21	7.99	
50%	2.43	16.04	

"quad" is one quadrillion BTU; approximately US$ 6.6 billion per quad of electrical energy.
Source: Ehrentraut et al. [13]/Springer Nature.

incandescent light bulb or compact fluorescent lamp (CFL). The efficiency of SSL products is almost three times better than CFL products and nine times better than that of an incandescent light bulb. Annual energy cost per lamp can be estimated as energy cost is 9.3 ¢/kWh, SSL product energy cost is US$ 1.81 compared to an incandescent light lamp of US$ 16.29 and a CFL product at US$ 6.25. These advantages alone captured much attention and ensured a strong future for LEDs [15]. As a result, this led to the LED industry's double-digit growth over the last decades.

The global LED lighting market size was valued at US$ 54.00 billion in 2019 and is projected to expand at a compound annual growth rate (CAGR) of roughly 11%. Growing stringency of regulations in terms of inefficient lighting technologies and rising government efforts toward sustainable development are the key growth drivers. An aggressive decline in the prices of LED, coupled with the transformation in energy policies across the world, has been a driving mechanism for market growth. Moreover, attractive incentives and rebates provided by the governments for the use of LED lighting in several countries will leverage the demand.

LEDs are highly efficient and reliable, and they yield a longer life span, which is anticipated to boost their application in both indoor and outdoor settings. These lights, at present, are the most cost-effective light, compared to incandescent lights, delivering around 100,000 hours of illumination with a small amount of energy consumed [16]. Their lower cost of operation and reduced heat losses make them a suitable alternative for incandescent lights. Technological advancements shift from conventional to green lighting, enhanced energy efficiency standards, and declining prices have also spurred product demand. As a whole, this clearly shows that the LED business had all the potential for explosive expansion. Many new inventions were seen in LED products and application technologies. Revolutionary LED growth in many areas can be seen as governmental and industrial funds were injected into technology research and development, thus whole supply chain of LED industry is expanding. In the Section 1.3, the LED industrial chain is further elaborated.

1.3 LED Industrial Chain

The LED industry can be divided into three sectors as shown in Figure 1.3. They are Front End (FE), Back End (BE), and LED Luminaire (LL) industries.

As illustrated in Figure 1.3, the FE industry consists of epitaxial growth and chip processing. Here, a thin layer of light-emitting material was grown on a suitable substrate, like sapphire for gallium nitride (GaN), gallium arsenide (GaAs) for aluminum indium gallium phosphate (AlInGaP), and aluminum indium gallium arsenide (AlInGaAs). Mostly, chips are grown in metal–organic chemical vapor

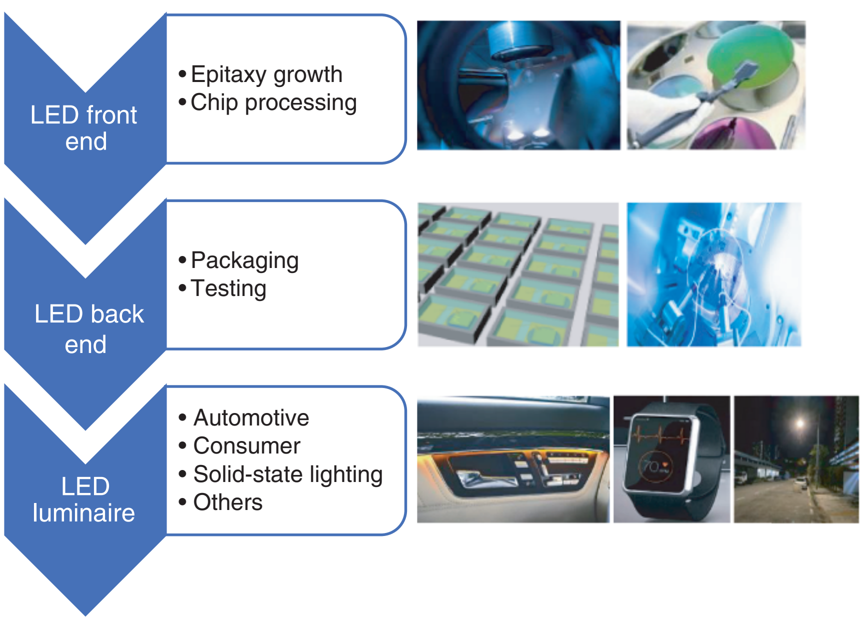


Figure 1.3 LED industrial chain. Source: Courtesy of ams OSRAM GmbH.

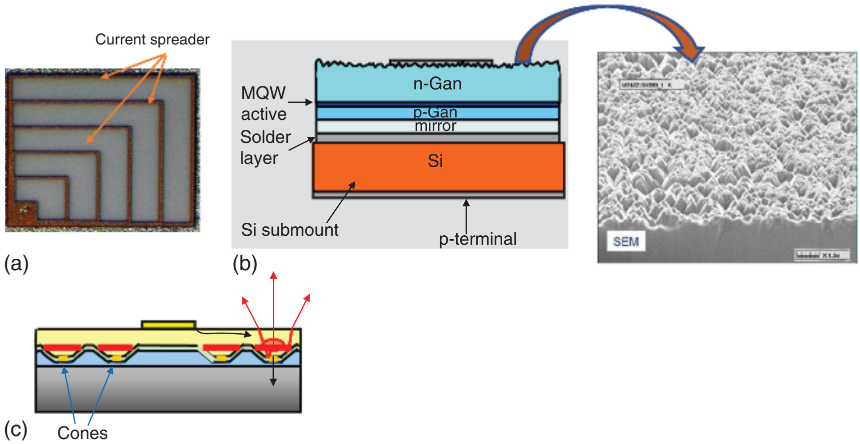


Figure 1.4 (a) AlInGaN chip top view showing current spreader, (b) AlInGaN chip cross-section view and roughened surface of chip surface, (c) AlInGaP and AlGaAs Thinfilm chip cross-section view showing reflector cones. Source: Courtesy of ams OSRAM GmbH.

deposition (MOCVD) reactors. The grown epitaxy wafers are further processed in chip processing processes where current spreaders are sputtered with gold layer to make an electrical connection at epitaxy n-layer that enables to bond for wire-bond at chip, as illustrated in Figure 1.4a.

For the AlInGaN chip, as illustrated in Figure 1.4b, the layer above epitaxy was roughened to improve light outcoupling. A passivation layer is introduced on top of this layer for protection. On the other hand, the AlInGaP and AlGaAs films grown on GaAs substrate go through a different process, especially those thin film technology chips in OSRAM, as illustrated in Figure 1.4c. To improve light extraction, reflector cones were fabricated in complex chip manufacturing processes. Right below these cones is a mirror to improve the reflection. The chips will be 100% tested and inspected for any defects before they are singulated into single chips. Once completed singulation, these wafers will be sent to Back Eng (BE) to package them into an LED product.

LED packaging processes consist of assembling the chip onto a package substrate using conductive or nonconductive glue, which is referred to as chip-bonding. It depends on the chip technology. Thin film chips are commonly glued using conductive inks, while sapphire chips are mostly glued using nonconductive glue. Flip chips, on the other hand, are soldered directly onto the package substrate. A package substrate can be premolded copper frame, ceramic, printed circuit board (PCB), or even metal can. Selections depend on the products end applications and thermal management requirements. Once the chip is attached to the package substrate, the anode is connected to the package by wire bonding process. In LED industries, gold wire was the preferred choice compared to silver or aluminum wire. Flip chip does not need such a wire bonding process, as its anode and cathode are directly soldered to package substrate. Packages with chip and bonded wire require physical protection; therefore, requiring encapsulation process. Encapsulation materials such as silicone, epoxy, or cap made of epoxy or glass will be used. Most of the package substrates are in panel or reel-to-reel (R2R) form. This substrate will be singulated to individual package in the singulation process after the encapsulation process. Here, the packaged LED is either diced via laser cutting or cut mechanically (either by sawing or trimming and forming) to make them into a single LED package for the next process, which are optical and electrical testing. All LED production is subjected to 100% testing and visual inspection to remove defective parts. The final process in BE is packing process. Here, the LEDs are either packaged in reels or trays, and they are vacuum-sealed in moisture barrier bags before being shipped to LED customers. Further details of the BE process will be explained in the LED manufacturing chapter later (Chapter 3).

LED is used in almost every industry, namely, in SSL, automotive, video walls, mobile phones, signage, medical industries, and many other applications. A few selected LED application industries are elaborated in Chapters 4–8.

1.4 Evolution in LED Packaging Technology

Ever since the industrialization of LED in the 1960s, the LED packaging has been evolving in synch with the application technology. It is revolutionized by the application itself. In the beginning, during late 1960s, LED was mostly used in signal lighting and indicators, for example, in signboards and calculators. The LED chips are packaged in lamp or Radial packages, as shown in Figure 1.5. However, the application is limited due to size and heat power dissipation capability of Radial package. Given this weakness, the Surface Mount Device (SMD) LEDs were born in early 1990s.

This opens up more new applications, especially in the automotive and consumer industries. With the invention of the super bright blue LED in the early 1990s and coupled with phosphor conversion technology from existing CFLs, white LED was invented by Nichia and OSRAM, thereby making tremendous impact on the LED lighting industry, especially in the general lighting application. There was an urgent drive to replace conventional lighting with LED-based lighting, which further provoked another wave of drive, in the packaging industry, as the applications demand higher brightness, specific radiation pattern, and variety of sizes. Hence, more variety of package designs were invented to meet the demands, as illustrated in Figure 1.5, where high-power packages and low-power packages evolved. As the LED lighting industry grows, another wave of innovation is triggered to drive miniaturization of the whole system in an application. This drives to integrate the LEDs with other components like ICs, lenses, diodes, and many other small components into one single package that calls System in Package (SiP). In parallel to the SiP, another drive happening while writing this book is to integrate at chip level, called System In Chip, SIC.

The LED packaging offers significant challenges for innovative designs to cater to customized applications. To meet these applications, one has to carefully carve the

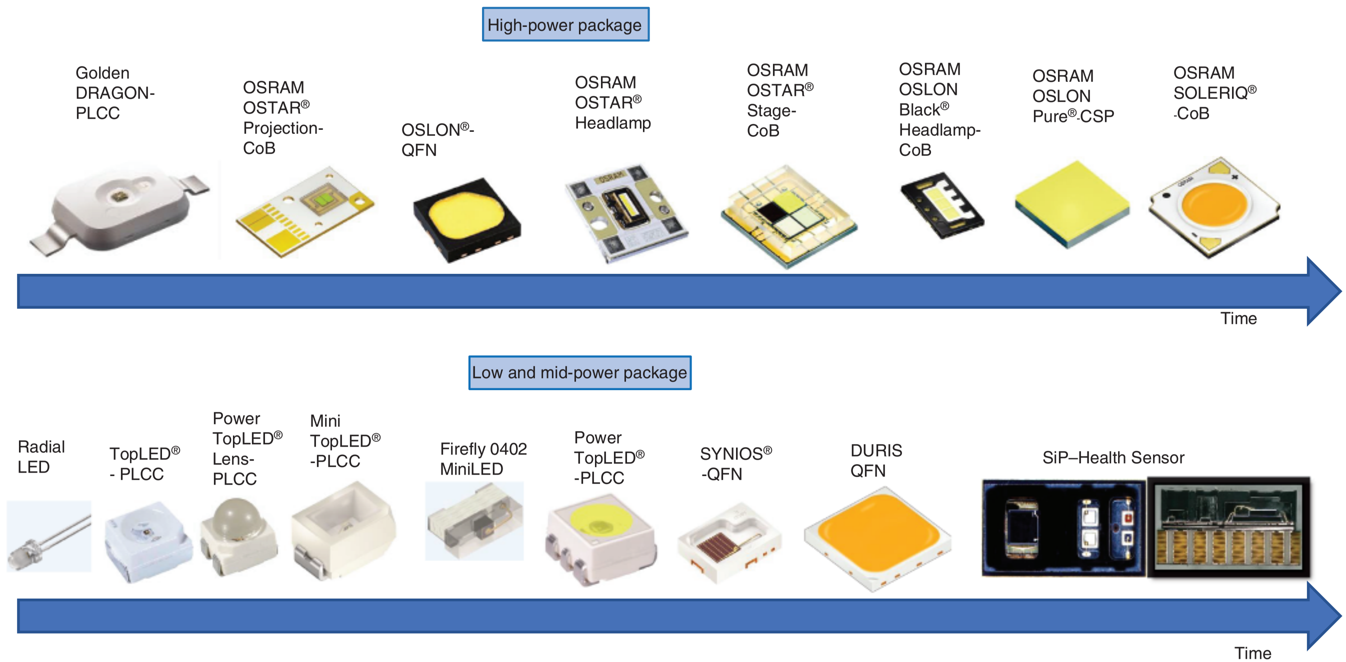
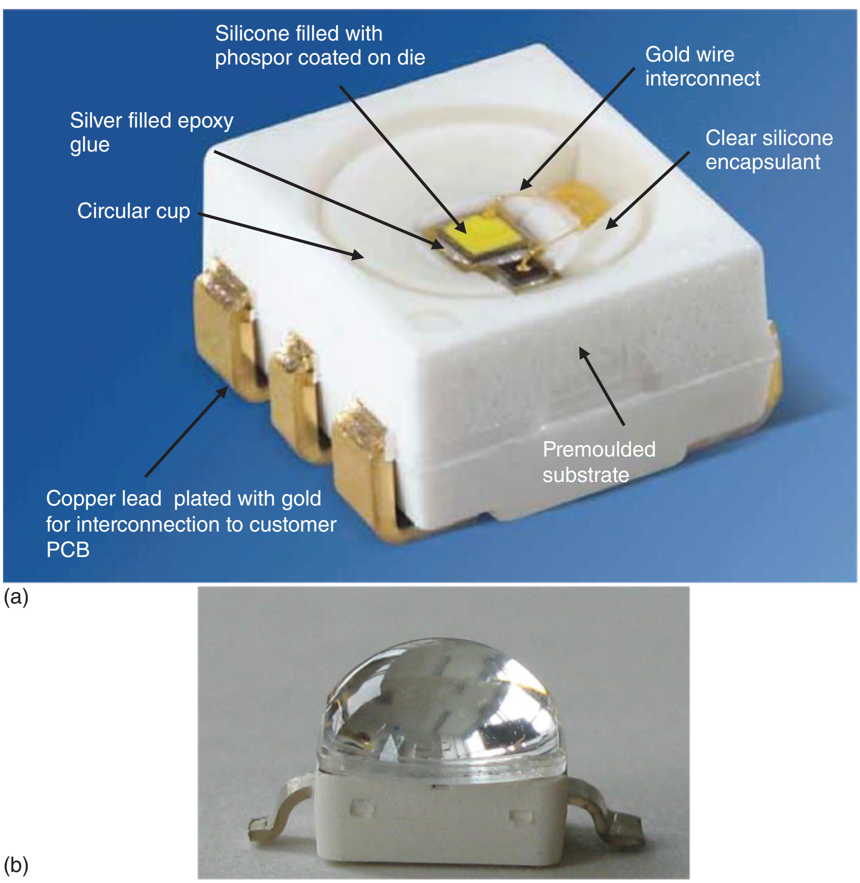


Figure 1.5 LED package evolution. Source: Courtesy of ams OSRAM GmbH.

design by considering the multidimensional space of options between the key components of a package, for example, the package substrate, interconnect, phosphor, optical interfaces, and in some cases, the special features of material like titanium oxide (TiO_2) layer.

The key success of an LED lies in the packaging technology that is able to fit the chip into specific applications. In fact, without a good package, the LED cannot be efficiently used for many applications. Why are the LED packages very important? As illustrated in Figure 1.6a,b there are many functions behind LED packaging. One of them is to interconnect interface with the customer. Second, it is the chip interconnect that is silver or gold-filled glue that adheres chip to the substrate (in this case, premolded package) and gold wire to connect the electrical circuit in the package. These chip, wire, and interconnect glue are sensitive to the environment, hence they need to be protected by the encapsulant. This encapsulant is made of either epoxy or silicone, which protects the chip from the environment and mechanical damages. Thirdly, the LED package offers the optical interface to the customer application.

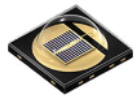
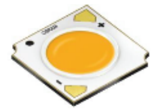
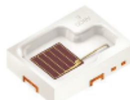
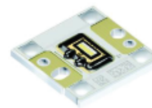


(a)

(b)

Figure 1.6 Illustrate a standard surface mount LED package. Source: Courtesy of ams OSRAM GmbH. (a) Power TopLED® – PLCC, (b) Golden Dragon® Lens – PLCC.

Table 1.2 General description of low-, mid-, high-, and ultra-high-power LEDs packages is in watts.

Low-power	Mid-power	High-power	Ultra-high-power
<0.2 W	0.2 W 1.0 W	1.0 W 4.0 W	>4.0 W
			
			

Source: Courtesy of ams OSRAM GmbH.

In Figure 1.6b, the cap's reflective properties shaping the radiation pattern are illustrated. In some packages, the lens on the top gives a unique radiation pattern for a specific application, for example, facial recognition in mobile phone security. It is important to identify the most competitive option for a distinct design-in, i.e. fitting to the technology roadmap of the customer application.

The packaging technology generally can be described in four categories, as in Table 1.2. They are low-power, mid-power, high-power, and ultra-high-power LED packaging. The electrical input power of these LEDs defines these categories, although without any governing standards. In general, LED package is considered as high-power when the electrical power is >1 W. But in a different case, chip sizes greater than 1 mm^2 were categorized as high-power. Mid-power is in the range of 0.2 to <1 W and the low-power <0.2 W.

In the end of 1960s to 1980s, most of the LEDs are in the form of Radial Through Hole LED package or metalcan package. It has its limitations in terms of size and thermal resistance. The LED chip has not matured enough for high drive current as the chip size is small and internal efficiency is still low. The LED was also not so bright. Furthermore, this package requires a through-hole PCB to solder to connect to the customer PCB circuit. This increases the size of the PCB. Hence, the end product or system size also follows the PCB size, which is relatively large. With all these limitations, much new research was taken place at some companies to develop a better package to meet the market demand. This was where the SMD LED was born. The SMD packaging in real sense was already in use in the non-LED semiconductor industry. As a result, there were many cross-learnings from the semiconductor industry to the LED packaging industry.

The SMD package technology has taken the LED to a new level of application. With the SMD package, the size, external lens design, and thermal management design can be more effective to bring in much value to the new application. As an example, having a cup and lens in the package will enable it to have better efficacy compared to no cup or lens, as the light will stray away or absorbed by the package and chip. On the other hand, with better heat sink, the LED package can bring down

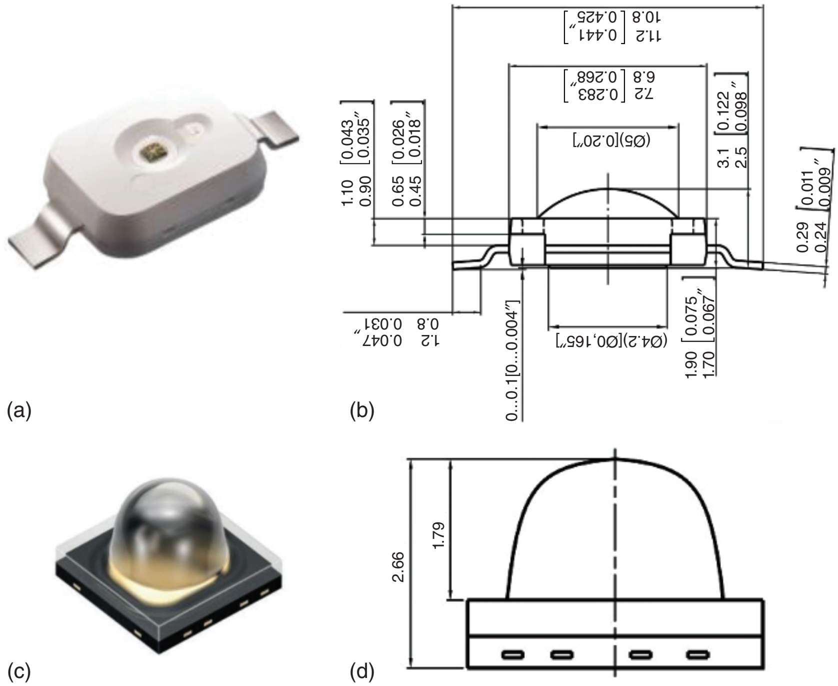


Figure 1.7 High-power packages: (a) Golden DRAGON package, (b) Golden DRAGON package schematic, (c) OSLON Black® package, and (d) OSLON Black package schematic. Source: Courtesy of ams OSRAM GmbH.

the real thermal resistance value significantly low. Example Golden DRAGON® of OSRAM in Plastic Leaded Chip Carrier (PLCC) package and OSLON® Black Series of OSRAM in the Quad Flat No-leads (QFN) package, as illustrated in Figure 1.7. They have real thermal resistance at typical values of 6.5 and 6 K/Wm^2, respectively. This enables the LED to be driven with high current and reap high efficacy and brightness of the LED without affecting the lifetime of the LED.

1.4.1 Low-Power Package Evolution

As mentioned earlier, the term low-power LED package referred to LED with electrical input power less than 0.2 W. These LEDs are usually driven at 5–50 mA with bias voltage in the range of 1.5–3.5 V. This voltage depends on its chip technology. Low-wavelength chips (GaN) have higher voltage compared to higher wavelength (AlInGaP and AlInGaAs) chips. For example, infra-red (IR) chips have voltage in the range of ∼1.5 V and blue ∼3.5 V. The chip size is usually in the range of 180–300 μm. The usual package constitutes of low-power LEDs are Radial lamp, small SMD top or side view PLCC packages, and ChipLED. The major applications of this package are mobile phone keypad and LCD backlighting. Besides, they are also used for backlighting for computer screens and TVs, signage, and large displays.

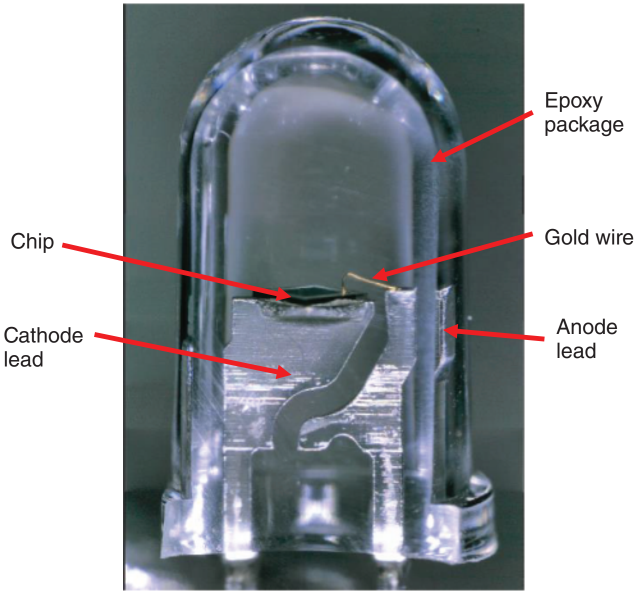


Figure 1.8 Radial package in a cross-section view.

In early days, most of the low-power LED packages are Radial packages as illustrated in Figure 1.8, which shows a simple LED package where the chip was bonded on copper lead and a gold wire connected between the chip and an anode lead. They are encapsulated by an epoxy material. The heat dissipation is mostly through the cathode lead. This is inefficient, however, sufficient for low-power applications.

The Radial LED package design could not progress well in the LED packaging technology due to its limitations. A smaller version of Radial LED was invented by Siemens Opto Semiconductors with narrow radiation pattern specifically for niche applications in sensor applications, for example, smoke detector sensors. In the early 1990s, Siemens Opto Semiconductors developed an SMD LED package, which is friendlier for the surface mount soldering process. It is a compacted LED package with a size of 3.4 mm by 3 mm and a height of 2.1 mm, and it improved the light outcoupling by a factor of 2 compared to Radial LED. It is cheaper than the Radial package. This was a breakthrough in an LED application. As brightness improved, lower cost and thermal resistance relatively lower than Radial package were achieved, and many newer applications of LED came. They are in automotive, traffic light signals, compact signboard, and handheld devices. Low-power LED packages in automotive are mostly used for brake lighting, signal lighting, and dashboard lighting. In the handheld device market, for example, handphones, in the mid-1990s, companies like Nokia, Siemens, Samsung, and Motorola drove the low-power LED package to a smaller size package. The low-power LED package size like Mini TopLED shrank to 2.3 mm by 1.9 mm with a height of 1.4 mm and ChipLED to mere 1 mm by 0.3 mm with a height of 0.57 mm for mobile phone keypad applications in the mid-1990s, before the smartphone era. This size further shrank as the application in Video Wall requires high pixel quality, where LED size and pitch size play an important role in Video Wall color gamut quality.

1.4.2 Mid-Power LED Packages

Mid-power LED packages are those packages that drive current from 50 to 150 mA and bias voltage between 1.5 and 3.5 V. The LED power is generally less than 1 W. Chip size is usually in the range of 300–600 μm. The package design is mostly PLCC packages like SMD top and side view LEDs and ChipLED. Some of the mid-power LEDs are shown in Figure 1.9. It comes in many sizes and forms that fit into the product application at the customer end.

Most of the applications are on TV, backlighting monitors, and automotive lighting on dashboard and interior lighting use mid-power LEDs. It is worth mentioning that many general lighting products use mid-power LEDs. This package can deliver high efficacy with manageable thermal loading. Their lower power consumption often allows standard PCB material, such as FR-4 PCB, to be used compared to the high-power LED package that requires metal-core PCBs. Figure 1.10 shows the mid-power thermal management design evolution. The thermal resistance or conductivity can be reduced significantly by having the heat sink at the package.

Figure 1.9 Some of the mid-power LED packages. Source: Courtesy of ams OSRAM GmbH.

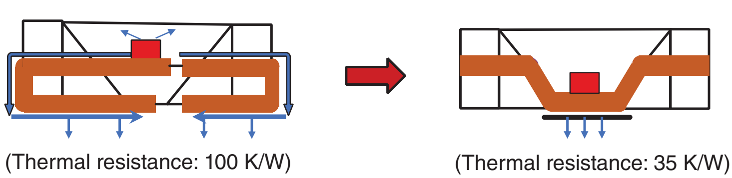


Figure 1.10 Mid-power LED PLCC package thermal management design evolution.

Many LED manufacturers, such as OSRAM Opto Semiconductors, Lumileds, Everlite, and Nichia, are significantly betting on this package category, and the cost of manufacturing in this package is significantly lower than high power, and indeed the market is significantly large.

1.4.3 LED High-Power and Ultra-High-Power Packages

The high-power LED packages are those with input power in the range of 1–4 W, and ultra-high-power packages are those with input power greater than 4 W. Their driving current is greater than 350 mA, and biasing voltage is in the range of 1.5–3.5 V. Chip size is usually in the range of 600–2000 μm. They can have either single large like OSRAM OSONIQ® P 7070 chip or multiple large chip like OSRAM Duris® S8. Some packages have multi-small chips arranged in an array in one package, for example, OSRAM SOLERIQ® S9. There are many types of packages namely single large chip packages; some are multi-chip packages. The package substrate varies. Some are premolded leadframe, ceramic, and metal-core PCB. Figure 1.11 shows the different varieties of high-power and ultra-high-power LED packages for different applications. There is single large die package like OSLON from OSRAM, XLamp XM-L3 from CREE, and K2 from Lumileds. Multiple large die size in a package like OSTAR series of OSRAM. Small/medium-sized die array in a package from Luminus and OSRAM. And single or multi very large die in a single package of Luminus or OSRAM.

The emergence of high-power LEDs is mainly due to the inability of low-power or mid-power packages to handle heat dissipation. For example, if the input power of an LED is 1 W, with a chip of internal efficiency of 50%, the heat generated in the LED will be roughly 0.5 W. This heat has to be dissipated from the chip efficiently and quickly. Failing to do so, the chip will have a significant impact on brightness and package reliability, and its lifetime will deteriorate. In many cases, the LED failed spontaneously. Figure 1.12 shows the high-power LED PLCC package thermal management design. It has big heat slug (sink) that allows the heat from chip to drain into the heat sink. The big heat slug also plays a role as a good thermal capacitance reservoir.

Beside the PLCC package, there is also ceramic package in high-power LED products. In Figure 1.13, there is an example from OSRAM that shows the OSLON®Square ceramic package. The substrate of this package is usually aluminum nitride, but there are also some cases made of silicon carbide. The thermal conductivity of silicon carbide is higher than that of aluminium nitride. This is ideal for high-power LED. However, the price of silicon carbide is relatively higher than aluminium nitride.

The die is attached to this ceramic substrate. On top of the die, a phosphor layer was attached. It was encapsulated using clear silicone. This encapsulant usually forms an optic to collimate the light at a certain viewing angle.

The LED high-power packages evolved mainly for automotive applications in the mid-1990s, where high-brightness LED makes a significant market differentiation in terms of aesthetic values, clarity, and elegance that charms end users. Luxury car makers such as Mercedes, BMW, Audi, and others are capitalizing on these values

Figure 1.11 High-power LED packages with a variety of solutions. Source: Courtesy of ams OSRAM GmbH and Courtesy of Luminus, Inc.

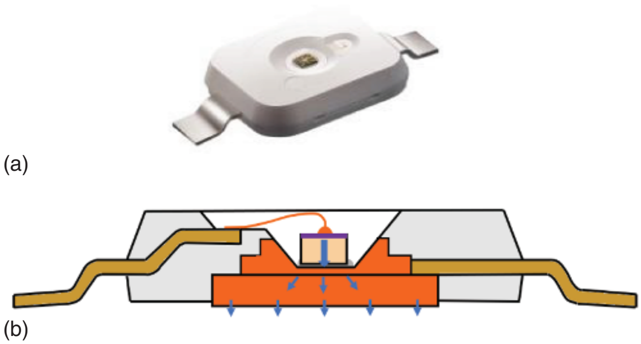


Figure 1.12 High-power LED PLCC package thermal management design: (a) Golden Dragon PLCC package. (b) Cross-sectional view of Golden Dragon PLCC package. Source: Courtesy of ams OSRAM GmbH.

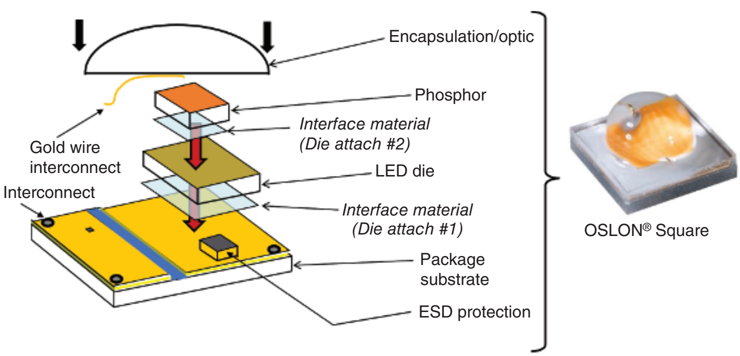


Figure 1.13 High-power LED package construction. Source: Courtesy of ams OSRAM Group.

to increase their sales. As a result, many of these large companies collaborated on research projects to develop new LED products that add value to end users. Some of the high-power packages that have evolved over the years are OSRAM Golden Dragon, Luxeon K2, Cree XLamp, Lumileds Rebel, OSRAM OSLON Square, OSRAM OSTAR, OSRAM OSLON Pure CSP, and SiP. Each is used for a specific application in the car, which will be further elaborated in a Chapter 2 and 4.

1.5 Summary

Light is one of the most essential elements for all living things. Humans mastered the science, technology, and engineering of artificial light over a period of time. This mastery has changed their lives and the course of evolution. The artificial light itself has evolved. The energy conversion efficiency of artificial lighting has changed from less than 1% to almost 80% in today's LED. The LED light has revolutionized human civilization. The LED application now covers almost every aspect of human life. The LED packaging plays a very important role to fit LEDs into all the applications that necessitate human wellbeing. It is the bridge between the LED chip and LED applications. The LED industry itself is still evolving. The LED's brightness increased as the need for high brightness increased. The LED packages evolved to support high brightness, where the package thermal management design was further perfected. The evolution further continues from single-component LED to a combined LED, sensor, IC, and passive component to a system packaging or system in a chip.

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