Solid-State Lighting Based on Light Emitting Diode Technology

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5.1 Historical Development of LEDs

More than 100 years ago in 1907, an Englishman named Henry Joseph Round discovered that inorganic materials could light up when an electric current flowed through. In the next decades, Russian physicist Oleg Lossev and French physicist Georges Destriau studied this phenomenon in great detail and the term ‘electroluminescence’ was invented to describe this. In 1962, inorganic materials (GaAsP) emitting red light were first demonstrated by Holonyak and Bevacqua [1] at General Electric’s Solid-State Device Research Laboratory in Syracuse, New York, although the light emitted was so weak that it could only be seen in a darkened room (by comparison, the efficacy of Thomas Edison’s first incandescent light bulb was 10 times greater). Since then, the efficiency of GaP and GaAsP advanced significantly in the 1960s and 1970s. The AlInGaP system was developed later, in the 1980s, and is now the basis of most high-efficiency LEDs emitting in the red-to-yellow visible region. The development of the nitride material system (GaN, InN, AlN and their alloys) in the last two decades has enabled efficient light emission to expand into the blue and green spectral region, and most importantly, allowing the production of white light (blue is the high-energy end of the visible spectrum and therefore enables the production of white light using blue light plus phosphors). Blue LEDs were made possible by a series of key breakthroughs in materials science summarised in Table 5.1, which will be discussed in greater detail later. In particular, the first bright blue LED was announced at a press conference on November 12, 1993 by Nakamura [2]. The invention of efficient blue LEDs has enabled white light source for illumination. In 1997, white light was demonstrated for the first time by combining a blue gallium nitride (GaN) LED with a yellow-emitting phosphor [3]. Such LEDs are called ‘white LEDs’.

Nowadays, solid-state lighting based on LEDs is already commercialised and widely used, for example, as traffic signals, large outdoor displays, interior and exterior lighting in aircraft, cars and buses, as bulbs in flash lights and as backlighting for cell phones and liquid-crystal displays. With the continuous improvement in performance and cost reduction in the last decades, solid-state

Table 5.1 A summary of the key steps in GaN-based LED development history

1938	Juza and Hahn [84]	The earliest polycrystalline GaN powder was synthesised by reacting ammonia with liquid Ga metal
1969	Maruska and Tietjen [92]	First single crystal GaN film was grown by chemical vapour deposition directly on a sapphire substrate
1972	Pankove et al. [102]	First blue GaN metal-insulator-semiconductor LED was reported
1986	Amano et al. [79]	Crack-free GaN films with good surface morphology and crystallinity were achieved by growing a thin AlN buffer deposited on sapphire at low temperature before GaN growth
1989	Amano et al. [43]	Amano, Akasaki and co-workers demonstrated that a low-energy electron beam irradiation treatment in a scanning electron microscope could cause a previously highly resistive Mg-doped GaN layer to show distinct <i>p</i> -type conductivity, enabling the first GaN <i>p</i> - <i>n</i> junction LED
1991	Nakamura et al. [38, 94]	Nakamura and co-workers showed that a ~20 nm thick GaN buffer layer deposited at low temperature (~500 °C) before the main GaN growth at ~1000 °C could also be used to grow smooth films on sapphire, including <i>p</i> -type material with good electrical properties
1992	Nakamura et al. [42]	Thermal activation of Mg-doped GaN to achieve <i>p</i> -type conductivity
1993	Nakamura et al. [97]	Blue and violet emitting double-heterostructure (DH) LEDs were successfully fabricated
1993	Nakamura et al. [2]	Nakamura announced the first bright blue LED at a press conference on November 12, 1993
1995	Nakamura et al. [95]	InGaN quantum well LEDs were fabricated
1997	Nakamura et al. [3]	White light was demonstrated for the first time by combining a blue gallium nitride (GaN) LED with a yellow-emitting phosphor

lighting has emerged to be a realistic replacement of incandescent and fluorescent lamps for our homes and offices.

Compared with any other existing lighting technology, solid-state lighting possesses two highly desirable features: (1) it is highly energy efficient with tremendous potential for energy saving and reduction in carbon emissions; (2) it is an extremely versatile light source with many controllable properties including the emission spectrum, direction, colour temperature, modulation and polarisation. The beneficial impact of LEDs on the economy, environment and our quality of life is so evident and well recognised that the 2014 Nobel Prize in Physics was awarded to the inventors of efficient blue LEDs: Isamu Akasaki, Hiroshi Amano and Shuji Nakamura.

5.2 The Importance of Nitride Materials

The main compound semiconductor materials used in LEDs and their bandgap energies are summarised in Fig. 5.1. For most optoelectronic devices such as light emitting diodes (LEDs), laser diodes, and photodetectors, a direct bandgap is essential for efficient device operation. This is because the optical emission processes in a semiconductor with an indirect bandgap require phonons for momentum conservation. The involvement of the phonon makes this radiative process much less likely to occur in a given timespan, which allows non-radiative processes to effectively compete, generating heat rather than light. Therefore semiconductors with an indirect bandgap are not suitable for efficient LEDs.

Conventional cubic III–V compound semiconductors, such as the arsenides and phosphides, show a direct-to-indirect bandgap transition towards higher energies. Therefore high-efficiency devices can be achieved in the infrared and red-to-yellow visible spectral regions, but the efficiency decreases drastically for

Fig. 5.1 Bandgap energies at 300 K of III–V compound semiconductors, plotted from data given in Vurgaftman et al. [4] and Vurgaftman and Meyer [5]. For the nitrides, the hexagonal a lattice constant has been used. The energy range corresponding to the visible spectrum is also indicated

conventional III–V semiconductors as the bandgap becomes indirect. In contrast, the nitrides have the hexagonal wurtzite structure, and the bandgap remains direct across the entire composition range from AlN to InN, with the bandgap energy covering a wide range from the deep ultraviolet to the infrared region of the electromagnetic spectrum. This makes the group-III nitrides system (consisting of GaN and its alloys with Al and In) particularly suitable for LEDs.

The blue/green and near-UV spectral regions can be accessed using the InGaN alloy, and today, the main application of the nitrides is in blue, green and white emitting LEDs, as well as violet laser diodes used for high-density optical storage in Blu-ray DVDs [6]. Since the InGaN bandgap energy spans the visible spectrum, extending into the infrared to ~ 0.7 eV for InN, this alloy covers almost the entire solar spectrum, and is thus a potential system for high-efficiency multi-junction solar cells [7].

The wide bandgap of the AlGaN alloy system will enable the fabrication of UV emitters and photodetectors. Possible applications of UV optoelectronics include water purification, pollution monitoring, UV astronomy, chemical/biological reagent detection and flame detection [8, 103].

AlGaN/GaN heterostructures are also suitable for electronic devices such as high electron mobility transistors (HEMTs), which have applications in microwave and radio frequency power amplifiers used for communications technology [9]. Such a wide bandgap materials system also allows device operation at higher voltages and temperatures compared to conventional Si, GaAs or InP-based electronics [10].

Although this chapter will be mainly focused on nitride-based LEDs for lighting applications, it is worth bearing in mind the great potential of nitride materials in other exciting applications mentioned above. And because of their unique materials properties and wide range of applications, group-III nitrides are widely considered to be the most important semiconductor materials since Si.

5.3 LED Basics

The simplest LED structure is a p – n junction, consisting of a layer of p -type doped semiconductor material connected to an n -type doped layer to form a diode with a thin active region at the junction. The principle for light emission in a p – n junction is illustrated in Fig. 5.2. The n -type region is rich in negatively charged electrons, while the p -type region is rich in positively charged holes. When a voltage is applied to the junction (called forward bias), the electrons are injected from the n -type region and holes injected from the p -type region across the junction. When the electrons and holes subsequently meet and recombine radiatively, the energy released is given out as light with an emission wavelength close to the bandgap of the material incorporated in the active region around the junction. For high efficiency, a heterojunction (consisting of two semiconductor materials with different bandgap) is usually preferred to a homojunction (consisting of a single semiconductor material) due to better carrier confinement, as shown in Fig. 5.2c, i.e. the electrons and holes are spatially confined together in the active region with lower bandgap energy, which increase the chance of radiative recombination to produce light.

For most high-efficiency LEDs, quantum wells (QWs) are routinely used in the active region, which provide additional carrier confinement in one direction, improving the radiative efficiency, i.e. the internal quantum efficiency (IQE). Quantum wells consist of a very thin (few nm thick) layer of a lower bandgap material, such as InGaN, between higher bandgap barriers, such as GaN (see Fig. 5.3). The QW active region is sandwiched between two thicker layers of n -type doped and p -type doped GaN for electron and hole injection, respectively.

■ **Fig. 5.2** A p - n homojunction under (a) zero and (b) forward bias. A p - n heterojunction under (c) forward bias. E_C , E_F and E_V are the conduction band, Fermi and valence band energy. Filled circle and open circle represent electrons and holes, respectively. In homojunctions, carriers diffuse, on average, over the diffusion lengths L_n and L_p before recombination. In heterojunctions, carriers are confined by the heterojunction barriers (after [11])

■ **Fig. 5.3** A schematic InGaN/GaN quantum well LED structure together with a high-resolution transmission electron microscope lattice fringe image of three InGaN quantum wells separated by GaN barriers

The recombination of electron and holes across the InGaN quantum well region results in the emission of light of a single colour, such as green or blue. We can change this colour by varying the composition and/or changing the thickness of the InGaN quantum well.

5.4 Fabrication of an LED Luminaire

The LED structure described above is the essential source of light, but it often makes up only a tiny volume fraction of the final application, such as an LED light bulb or luminaire. Figure 5.4 illustrates the fabrication procedures involved in making an LED luminaire. The first step is the deposition of the nitride LED structure on a suitable substrate wafer such as sapphire, SiC, Si or GaN. This is performed by crystal growth usually via a process called metal organic vapour phase epitaxy (MOVPE) in a heated chamber or reactor. After deposition, these epiwafers will be processed into LED devices according to the LED chip design, which usually involves several steps including wafer bonding, *n* and *p*-type contact patterning, etching, metallisation and surface roughening. The processed LED devices are then separated via cleaving, sawing or laser cutting into individual dies. Depending on the target applications, these individual LED dies are mounted on an appropriate package in a form compatible with other electronic components such as drivers. For white LEDs, phosphors will also be incorporated into the package, together with blue-emitting LED dies in most cases. These packaged LED devices are then ready to be used as the light source in a luminaire.

From the fabrication procedure, we can see that there are many components contributing to the overall efficiency of a packaged LED device. These can be broken down into:

Fig. 5.4 Illustration of the fabrication procedures involved in making LED luminaries. The corresponding efficiency and losses involved in each procedure are also listed

1. Internal quantum efficiency (η_{IQE})
2. Light extraction efficiency from the chip (η_{LEC})
3. Electrical efficiency (η_{EE})
4. Phosphor conversion efficiency (η_{conv})
5. Light extraction efficiency from the package (η_{LEP})

The IQE is defined as the number of photons emitted from the active region divided by the number of electrons injected into the active region. The IQE is primarily determined by the LED structure design, such as the choice of material compositions, layer thicknesses, doping profile; and for a given structure, the material quality linked to the growth conditions used during the epitaxy procedure. The IQE is also a function of the current density through the LED. At high current density the IQE falls, a phenomenon known as ‘efficiency droop’.

The light generated in the quantum well region needs to be extracted from the semiconductor material: most III–V semiconductors have high optical refractive indices (GaN: $n \sim 2.4$; InGaP: $n \sim 3.5$), and only a small portion of the light generated in the quantum well region can escape. This is because much of the light is trapped inside the LED by total internal reflection. Various advanced chip designs have been developed and used during the wafer and die level fabrication procedures to increase the possibility of light extraction from LED chips (LEC) and to minimise the electrical losses caused by the electrical contact and series resistances. Today, an LEC value $>85\%$ is achieved for high performance commercial LED devices with a ThinGaN chip structure, as shown in [Fig. 5.5b \[12\]](#).

Furthermore LED dies need to be packaged before they can be incorporated with other electronic components in a real application. LED packaging is also critical to achieve high luminous efficiency, dissipate heat generated from the LED chip, improve reliability and lifetime and control the colour for specific requirements, as well as to protect the LED chips from damages due to electrostatic discharge, moisture, high temperature and chemical oxidation. A schematic structure of a high power LED package is shown in [Fig. 5.5a](#), together with a picture of a commercial white LED package shown in [Fig. 5.5c](#). The light extraction efficiency from a package (LEP) such as this is as high as 95% . For white light generation, a yellow-emitting cerium-doped yttrium aluminium garnet (YAG) phosphor plate is added on top of the nGaN layer. To achieve a high phosphor conversion efficiency, the phosphor material is carefully chosen to match the LED emission for optimum excitation.

5.4.1 Efficiency and Efficacy

For a single colour LED such as blue, green and red LEDs, wall-plug efficiency is usually used as a measure of the overall efficiency. The wall-plug efficiency, measured by the light output power (measured in watts) divided by the electrical input (also in watts), is dimensionless and is usually expressed as a percentage. For white LEDs, a different term, efficacy, is usually used instead of efficiency. The unit of efficacy is lumens per watt (lm/W), corresponding to light power output (as perceived by the human eye and measured in lumens) relative to electrical power input (measured in watts). The terms efficiency and efficacy are both widely used in lighting, and care must be taken not to confuse them. The efficacy of a white light source will be explained in more detail later in this chapter. The term efficacy takes into account the sensitivity of the human eye to different colours: it is a maximum for green light at 555 nm.

It should also be noted that the efficiency or efficacy of a luminaire would be lower than the packaged LED devices due to additional losses caused by other

Fig. 5.5 (a) The schematic structure of a high-power LED package with good optical efficiency and thermal management, as required for high power LED chips. (b) Cross-section of a high power ThinGaN LED chip, illustrating the complex structure of state-of-the-art white LEDs for illumination. (c) A picture of a high power white LED package from Osram

components such as optics, heat sinks and electrical drivers. When discussing the efficiency of LED lighting, it is important to be clear about the form of the light source: whether it is a bare die, packaged LED device or luminaire.

The performance of LEDs has improved dramatically over the last decade with sustained improvements in the material quality, LED structure, chip design and packaging. Before moving to the discussions on LED performance and applications, it is worthwhile to first review the historical development of nitride LEDs, in particular the research challenges involved.

5.5 Research Challenges

The research in nitride materials and LED devices is a very broad and interdisciplinary field, spanning crystal growth, physics, materials science and characterisation, device processing, device physics, luminaire design and others. From a materials science point of view, nitride materials are highly defective compared with conventional semiconductor materials such as Si and GaAs, and the remarkable success of nitride-based LEDs is based on a series of wonderful achievements in science and engineering.

5.5.1 Crystal Growth

As with many other semiconductor materials, III-nitrides do not exist naturally, so the crystals need to be grown by some chemical reaction. The predominant growth method for the group-III nitrides is metalorganic vapour phase epitaxy (MOVPE, also called metalorganic chemical vapour deposition, MOCVD), both for research and mass-production of devices such as LEDs and lasers.

It should be noted that one key difference between the nitrides and the other III–V compound semiconductors mentioned earlier in this chapter is the lack of a suitable substrate for heteroepitaxial growth (namely, crystal growth on a different substrate material) of GaN. Bulk substrates of GaAs, GaP and InP can be used for epitaxy of most of the III–Vs and even II–VI compounds. Unfortunately, the nitrides have very high melting temperatures and dissociation pressures at melting, ~2800 K and ~40 kbar, respectively, for GaN, which means that bulk crystals cannot be grown from stoichiometric melts using the usual Czochralski or Bridgman methods [13,14]. Not only have bulk substrates of GaN been unavailable in a sufficient size and at reasonable cost, there is also no other suitable substrate material with a close lattice match to GaN. The properties of the GaN epitaxial layer such as crystal orientation, defect density, strain and surface morphology are to a large extent determined by the substrates used. Most commercial GaN-based LEDs are grown on sapphire or silicon carbide (SiC) substrates. Recently, the use of large area Si substrates has attracted great interest because high quality Si wafers are readily available in large diameters at low cost [106]. In addition, such wafers are compatible with existing sophisticated automated processing lines for 6 inch and larger wafers commonly used in the electronics industry.

Sapphire was the original substrate material, and remains the most commonly used to this day, but it has a lattice mismatch of 16 % with GaN. This is so large that attempts at direct epitaxial growth inevitably result in rough surface morphologies and a very high density of defects called dislocations that thread up through the growing layer: a typical density of such dislocations passing through the active InGaN quantum well region is five billion per square centimetre ($5 \times 10^9 \text{ cm}^{-2}$), as shown in ■ Fig. 5.6.

The development of growth techniques for the reduction of the threading dislocation (TD) density in GaN on sapphire has resulted in considerable improvements. There are numerous methods in the literature, mostly related to the annealing of a low temperature nucleation layer [15], island formation and subsequent coalescence, as detailed in Figge et al. [16] and Kappers et al. [17,18]. An example of TD reduction using an SiN_x interlayer is shown in ■ Fig. 5.7. The mechanism by which TD density can be reduced is as follows: the thin SiN_x interlayer constitutes a mask containing random holes through which small faceted GaN islands form on regrowth; aided by the inclined facets of the islands, the TDs bend laterally and react with other dislocations to annihilate and form half loops, hence halting their upward propagation, as illustrated in ■ Fig. 5.7a. It was also found that the growth conditions of the GaN regrowth on top of the SiN_x interlayer have a pronounced effect on the degree of the TD reduction. By using a special 'slow' coalescence method, the TD density of the seed layer ($5 \times 10^9 \text{ cm}^{-2}$) was reduced to $5 \times 10^8 \text{ cm}^{-2}$ and successively deployed SiN_x interlayers reduce the TD density further to $1 \times 10^8 \text{ cm}^{-2}$, as shown in ■ Fig. 5.7b.

Dislocations are known to be non-radiative recombination centres [19] that should strongly quench light emission. Indeed, if the dislocation density in other semiconductors, for example, GaAs, exceeds around 1000 per square centimetre (10^3 cm^{-2}), the operation of light emitting devices is effectively killed. However, commercial InGaN blue and white LEDs show high performance despite the fact

Fig. 5.6 Transmission electron microscopy (TEM) images showing the high density of threading dislocations resulting from the growth of GaN on sapphire substrate. The lattice mismatch between GaN and (0001) sapphire is 16 %, which gives rise to a dislocation density in the GaN of typically $5 \times 10^9 \text{ cm}^{-2}$, unless dislocation reduction methods are used

Fig. 5.7 (a) Cross-sectional TEM image of an SiN_x interlayer (arrowed) deposited on a GaN seed layer followed by the regrowth of GaN islands. Threading dislocations can be observed as bright lines in the image. (b) Weak beam dark field TEM image, $g = (11-20)$, showing the reduction of edge and mixed TDs with successive SiN_x interlayers and a 'slow' coalescence of GaN between the layers

that the TD density of such devices is usually in the range of 10^8 cm^{-2} . The reason that InGaN LEDs are much more tolerant of TDs than other conventional III-V materials is probably due to carrier localisation effects [20–26]. The first contributing factor is the monolayer height interface steps on the InGaN quantum wells. Since the QWs are strained and because of the high piezoelectric effect in GaN, a monolayer interface step produces an additional carrier-confinement energy of about $2k_B T$ at room temperature, where k_B is the Boltzmann constant and T is the temperature. This is sufficient to localise the electrons. Recent three-dimensional atom-probe studies also confirmed that InGaN is a random alloy. Calculations show that random alloy fluctuations on a nanometer scale strongly

localise the holes at room temperature. Thus, the above two mechanisms can localise both the electrons and the holes, reducing diffusion to non-radiative defects like TDs. It is interesting to note that the electrons and holes are localised by different mechanisms in InGaN quantum wells.

Although high threading dislocation densities seem to be not very detrimental for InGaN LEDs, laser diodes and AlGaIn-based UV-emitters do show a strong dependence of lifetime on dislocation density. Moreover, the growth conditions will also affect many microstructural properties of nitride materials as well as impurity levels and thus the final device properties. Therefore, the research in crystal growth remains highly relevant and important for high performance devices.

5.5.2 Internal Electric Field

The nitrides normally crystallise in the hexagonal wurtzite structure, which is non-centrosymmetric and has a unique or polar axis along a certain direction (the c -axis). Since the bonding is partially ionic due to the difference in electronegativity of the group III and V atoms, a spontaneous polarisation will exist in the crystal because of the lack of symmetry. In addition, most nitride devices involve the use of strained heterojunctions, such as InGaN/GaN. Because the in-plane lattice constant of InGaN is larger than for GaN, the InGaN layer will be under compressive strain perpendicular to the c -axis and under tensile strain along the c -axis when grown epitaxially on GaN. An applied strain along or perpendicular to the c -axis will cause an internal displacement of the metal sublattice with respect to that of the nitrogen, effectively changing the polarisation of the material. This strain effect provides an additional contribution to the polarisation of the material, referred to as the piezoelectric component, and is particularly relevant to strained heterostructures.

Virtually all commercial GaN-based LEDs are grown along the c -axis of the crystal. Since this is a polar direction, there exists an electric field across the InGaN quantum well due to a difference in polarisation for the well and barrier material. The electric field will cause a tilting of the conduction and valence bands in the well, separating the electrons and holes and shifting the quantum well emission wavelength to lower energy, as illustrated in ■ Fig. 5.8. This is known as the quantum confined stark effect (QCSE).

There are some general observations about the QCSE relevant to nitride QWs: with the presence of an electric field, the transition energy is shifted to a lower value (from $\Delta E_{g,QW}$ to ΔE_{gl}) and this shift is roughly equal to the sum of the shifts of the first electron (ΔE_{e1}) and hole (ΔE_{h1}) levels; it is the hole state that contributes most due to the larger effective mass; electrons and holes are separated from each other spatially by the electric field across the quantum well, resulting in a reduced overlap of electron and hole wave functions and thus a longer radiative lifetime; wider wells (QW2) show more obvious effects of the QCSE and a larger potential drop (ΔE_{E2}) across the well. For a sufficiently wide well, the emission can be lower energy than the bandgap of the quantum well material itself.

The impact of the internal field, especially the piezoelectric field caused by strain, on quantum well recombination behaviour has been confirmed experimentally and reported in various III-nitride-based heterostructures [27–32]. Redshifts of emission energy and lower emission intensity were found in strained quantum wells based on III-nitrides, confirming the strong influence of the strain-induced piezoelectric field. However, with increasing carrier injection, a blue shift of the emission peak was observed by several researchers [33,34] and attributed to the reduction of the QCSE due to the in-well field screening by carriers. Therefore, in

Fig. 5.8 Schematic plot showing the effects of the QCSE on InGaN/GaN quantum wells: *black*: QW1 without electric field; *blue*: QW1 with electric field; *red*: QW2 (thicker quantum well) with electric field

Fig. 5.9 Schematic of the principle polar, non-polar and semi-polar planes of GaN. The QCSE effect should be eliminated by growing along a non-polar direction such as $[1-100]$ and $[11-20]$ or minimised along a semi-polar direction such as $[11-22]$

an LED structure, the electric field across the quantum wells is not only determined by the polarisation field but also affected by the carrier density and distribution in the quantum well region. The carriers may be from carrier injection (optical or electrical), as well as from doping, either intentional dopants or non-intentional impurities.

From the discussion above, it is obvious that the QCSE is not desirable for LEDs of high efficiency and good colour consistency. Figure 5.9 shows the main polar, non-polar and semi-polar planes of GaN. In principle, the QCSE should be eliminated by growing along a non-polar direction such as $[1-100]$ and $[11-20]$ or minimised along a semi-polar direction such as $[11-22]$. The efficiency of non-polar and semi-polar light emitting structures is therefore expected to be enhanced over that of polar.

However, it was found that the defect density is currently much higher in GaN structures grown in such directions [35], unless expensive freestanding non-polar or semi-polar GaN substrates are used [36]. Furthermore, the indium incorporation in the InGaN MQWs grown along non-polar direction is 2–3

times lower than along the *c*-plane for similar growth conditions [37]. The output power of the non-polar LEDs also reduced dramatically when the emission wavelength was longer than 400 nm. Therefore, a non-polar plane is considered not suitable for LEDs with emission wavelengths longer than blue and semi-polar planes are preferred for blue, yellow and red LEDs with reduced internal field, but again high defect densities are a problem. Despite the potential advantages of reduced internal field, non-polar and semi-polar LEDs are currently not commercially viable due to their lower overall performance and the requirement of expensive freestanding GaN substrates.

5.5.3 *p*-Type Doping

For III-nitrides, *p*-type doping is problematic and the realisation of *p*-type conductivity was another major breakthrough in the historical development of nitride-based LEDs. Non-intentionally doped GaN usually shows *n*-type conductivity; however, the improvement in crystal growth methods has managed to reduce this background doping level sufficiently to allow controllable *p*-type doping [38]. Many potential *p*-type dopants have been tried and so far magnesium is the most successful *p*-type dopant for GaN, AlGaIn and InGaIn with low Al and In mole fractions.

There are two main issues involved in Mg doping: (1) the presence of hydrogen in MOVPE and HVPE growth environments results in the passivation of Mg by forming Mg–H complexes that are electrically inactive; (2) Mg forms relatively deep acceptor states ~160–200 meV above the valence band [39], resulting in only a small fraction activated at room temperature and therefore low conductivity of *p*-type GaN. This means the hole concentration will always be more than an order of magnitude lower than the Mg concentration. Furthermore, heavily Mg-doped GaN is subject to self-compensation due to the formation of donor-like structural defects [40].

The first issue can be solved by thermal annealing under an N₂ ambient at a temperature higher than 700 °C [41,42] or by electron beam irradiation [43] to activate the passivated Mg. The thermal annealing technique has become the standard method for dopant activation because it is straightforward, reliable and can be implemented in-situ, within the MOVPE growth reactor. In contrast, the second issue of a deep acceptor level and self-compensation is intrinsic and is the main reason limiting the hole concentration. ■ Figure 5.10 shows the

■ Fig. 5.10 Hole density in GaN:Mg films as determined by the Hall effect versus the Mg concentration of the films as measured by SIMS. Data from Obloh et al. [44]

■ **Fig. 5.11** Calculated valence band diagram for the Mg-doped $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ superlattice with spontaneous and piezoelectric polarisation fields taken into account. The dashed line indicates the Fermi energy and the circles represent the energy of the Mg acceptor with solid circles indicating the ionised form. The growth direction for normal Ga-polarity material would be from left to right. Data from Kozodoy et al. [46]

concentration of free holes at room temperature in Mg-doped GaN by MOVPE [44]. The hole concentration reaches its maximum value of about 10^{18} cm^{-3} for a Mg concentration of about $3 \times 10^{19} \text{ cm}^{-3}$, and thereafter decreases with further increase of Mg doping.

A promising method to achieve higher acceptor activation and lower electrical resistivity is to use AlGaN/GaN superlattices. This provides a periodic oscillation in the valence band edge, allowing ionisation of acceptors in the wide bandgap AlGaN layers to provide hole accumulation in the adjacent GaN layers, leading to an overall increase in hole concentration [45]. The principle is illustrated in ■ Fig. 5.11, where it is apparent that polarisation fields in the nitrides enhance the band edge modulation, leading to parallel sheets of highly concentrated free carriers where the Fermi level intersects the valence band [46]. This can result in spatially averaged hole concentrations in the 10^{18} cm^{-3} range for such superlattices [47,48]. Using the same approach, *p*-type conductivity in $\text{Al}_{0.17}\text{Ga}_{0.83}\text{N}/\text{Al}_{0.36}\text{Ga}_{0.64}\text{N}$ superlattices has been demonstrated [49], and this will undoubtedly be a common approach in deep-UV emitting LEDs where *p*-type AlGaN is even more problematic due to wider bandgaps.

Although the development of *p*-type doping has enabled high-efficiency semiconductor devices, the hole carrier concentration in a GaN-based LED device is still about two orders of magnitude lower than the electron concentration, resulting in a large asymmetric carrier distribution in the active region. *P*-type doping in GaN and its alloys with InN and AlN remains a topic of interest at both a fundamental science level and in technological aspects.

5.5.4 Green Gap and Efficiency Droop

In spite of the challenges mentioned above, the performance of nitride LEDs has continued to advance, and devices emitting in the violet to green spectral region have already been commercialised. The highest efficiencies are still achieved for

■ Fig. 5.12 Plot of the external quantum efficiency (EQE) of commercial LED devices measured using EL at 350 mA, showing the issue of the ‘green gap’

■ Fig. 5.13 Plot of the external quantum efficiency (EQE) and light output of commercial blue and green emitting LED devices measured using EL at different forward current, showing the issues of ‘efficiency droop’ at higher current density

blue and violet wavelengths, and despite considerable research efforts (both academic and industrial), a rapid drop in performance towards deep green (the ‘green gap’) and UV wavelengths remains (■ Fig. 5.12). Another important problem is that the efficiency of InGaN-based LEDs decreases with increasing current density, an effect known as ‘efficiency droop’ (■ Fig. 5.13). Solving the ‘green gap’ and ‘efficiency droop’ problems is currently a key focus for research both in academia and industry [12,50–56].

For AlGaInP LEDs, the reason for the lower efficiency at wavelengths shorter than 600 nm is the transition from a direct to an indirect bandgap, as shown in ■ Fig. 5.1. The factors limiting the IQE of nitride LEDs are complex and not well understood. For InGaN, the reason for decreased efficiency in the green spectral region has been attributed to the miscibility gap between GaN and InN [57] and

high polarisation fields caused by the increasing strain with higher InN mole fractions.

Possible mechanisms of ‘efficiency droop’ that have been proposed include Auger recombination [52,56], high defect density [54,58], carrier leakage [59], polarisation-induced built-in electric fields at hetero-interfaces [60,61], poor *p*-type conductivity [62,63] and carrier delocalisation at high current densities [64]. In order to reduce the current density and thus the efficiency droop, a thicker single quantum well has been proposed to replace thin multiple quantum wells as the active region [12]. However, it was found that thicker InGa_N QWs are only feasible in the short wavelength range around 400 nm. For LEDs emitting at longer emission wavelengths, the material quality decreases due to growth at lower temperatures and the internal field rapidly increases due to higher In contents. Therefore, most commercial blue- and green-emitting LEDs still use thin multiple quantum wells as the active region.

5.5.5 Chip Design

The discussions above on crystal growth, *p*-type doping, internal fields and efficiency droop are mainly concerned with how to improve the internal efficiency of GaN-based LEDs by optimising the material growth and the structure design. However, improving the generation of light in the active region alone is not enough to achieve an efficient LED device, because the overall efficiency of an LED device is determined by many components as mentioned earlier in this chapter. Chip design is an important area of research to reduce internal reflection for higher light extraction and to enable uniform current injection (especially hole injection). The schematic structures of several different chip designs developed over the years are illustrated in ■ Fig. 5.14.

Compared with the *n*-type region, the *p*-type layer is very resistive and of limited thickness. To overcome the current spreading problem, a semi-transparent NiAu contact was originally deposited over the *p*-Ga_N [66] for a conventional shape LED chip. However, this approach results in significant losses when the emitted light passes through the *p*-contact. The ‘Flip-chip’ (FC) approach was then developed, where the LED chip is inverted and the light is emitted from the *n*-Ga_N side. In this approach, the NiAu contact is replaced by a thick and reflective contact, usually comprising silver, to reflect back the light emitted towards the *p*-type layer side [67]. In order to overcome the internal reflection problem, laser lift-off of the sapphire substrate and *n*-Ga_N roughening were used in the thin-film flip-chip (TFFC) LED design, achieving light extraction efficiency as high as 80 % by 2006 [68]. A similar vertical thin-film device (VTF) was also developed, resulting in an estimated light extraction efficiency of 75 % [69]. In recent years, patterned sapphire substrates have become very popular due to the advantages of improved material quality and ease of light extraction. Combining patterned sapphire substrates with an indium-tin-oxide (ITO) current spreading layer, a light extraction efficiency as high as 88 % was estimated [70] for this PSS-ITO approach.

The above approaches all extract the emitted light primarily from the top or bottom side of the LED chip. When a bulk Ga_N substrate is used, the sidewalls of the LEDs can be used to extract part of the light through geometric die shaping, as shown in ■ Fig. 5.15. These volumetric LEDs have the potential to achieve even higher light extraction efficiency than thin-film LEDs based on modelling [71]. Today, light extraction efficiencies exceeding 85 % are achieved for high power TFFC InGa_N LEDs [12]. When using Ga_N as a substrate, the light extraction efficiency can also be as high as 90 %.

Fig. 5.14 Schematic cross sections of various GaN-based LED chip designs: (a) Conventional chip. (b) Flip-chip (FC). (c) Vertical thin film (VTF). (d) Thin-film flip-chip (TFFC). (e) Patterned sapphire substrate combined with ITO contact (PSS-ITO). (f) GaN substrate volumetric LED chips. After Nakamura and Krames [65]

5.5.6 Generation of White Light with LEDs

Whereas LEDs emit light of a single colour in a narrow wavelength band, white light is required for a huge range of applications, including LED backlighting for large LCD displays, and general home and office lighting. White light is a mixture of many colours (wavelengths) and there are two main methods to generate white light using LEDs: Phosphor method and RGB method, as illustrated in Fig. 5.16.

The first commercially available white LED was based on an InGaN chip emitting blue light at a wavelength of 460 nm that was coated with a cerium-doped yttrium aluminium garnet (YAG) phosphor layer that converted some of the blue light into yellow light [72]. Nearly all white LEDs sold today use this method. The phosphor layer is sufficiently thin that some blue light is transmitted through it, and the combination of blue and yellow produces a ‘cool white’ light.

Fig. 5.15 (a) Scanning electron microscope image of a fabricated triangular-shaped gallium nitride on gallium nitride (GaN-on-GaN) LED chip with roughened top and side surfaces. (b) Corresponding device geometry. Unlike cuboidal shapes, light is not trapped inside by total internal reflection with this geometry. Reprinted with permission from David et al. [71]. Copyright 2014, AIP

Fig. 5.16 Illustration of white light generation using phosphor method (blue/UV LEDs + phosphors) and using RGB method (Red + Green + Blue LEDs)

This is fine for many applications (displays, lighting in cars, buses, yachts and cell phones back lights), but the quality of light is probably not good enough for home lighting, for which a warmer white light containing some red light is desirable. To generate ‘warm white’, red phosphors are typically added [73].

Since the efficiency with which existing red phosphors are excited using blue light is much less than that using near-UV light, a better route to generate ‘warm white’ light might be to use a near-UV LED plus red, green and blue or more coloured phosphors. Thick phosphor layers would be used so that no near-UV light from the LED would be transmitted in much the same way as the phosphor coating on fluorescent tubes and CFLs prevents the transmission of UV light. The drawback of this method is the large intrinsic energy loss from converting a near-UV photon to a lower energy visible photon.

Mixing red and green and blue (RGB) LEDs is an alternative way to produce white light without using phosphors, which is potentially the most efficient. However, there are three basic problems with this method. The first is that the efficiency of green LEDs is much less than that of red and blue, for reasons that are not yet understood (this is known as the ‘green gap’ problem described earlier). Hence the overall efficiency of this method is limited by the low efficiency of the green. Second, the efficiencies of red, green and blue LEDs change over time at different rates. Hence if a high quality white light is produced initially, over time the quality of the white light could degrade noticeably. However, this process is

slow and can be corrected electrically using automatic feedback. Third, because the emission peaks of LEDs are narrower than those of most phosphors, red plus green plus blue LEDs will give a poorer colour rendering than by using phosphors. This problem can be minimised by a careful choice of LED emission wavelengths, and of course, more than three different colour LEDs can be used for better coverage of the visible spectrum. In particular, using four LEDs (red, yellow, green and blue) can give a good colour rendering, although at the expense of increased complexity.

5.5.7 LED Packaging

LED packaging secures and protects the LED chips from damage caused by electrostatic discharge, moisture, high temperature and chemical oxidation. When designing the LED package, the issues involved in optical control, thermal management, reliability and cost need to be addressed simultaneously. The main package components include the LED die/chip, electrodes (anode and cathode), bond wire (connecting the LED die and electrodes), heat sink (removing heat generated by the LED die), phosphor coating (for white light emission) and primary lens (for directing the light beam).

Many solutions have been developed over the years for high power LED packages, as shown in ■ Fig. 5.17, ranging from single large die packaging with input powers of 1–2 W to chip-on-board and ‘Jumbo Die’ solutions that can take input powers up to 94 W with lumen flux higher than 10,000 lm from a single package. Depending on the application, different LED package sizes and powers would be required. An interesting trend of LED packaging is to move from chip-based packaging to wafer-level packaging, with advantages of higher packing density, ease of integration on circuit boards, higher current density and higher reliability.

■ Fig. 5.17 Wide variety of solutions for high power LED packages. Images from Philips Lumileds, Osram, Cree and Luminus

5.6 LEDs for Lighting

Over the last decade, advances in the material quality, LED structure, chip architecture and package design have improved the performance of LEDs dramatically in terms of light quality, efficiency/efficacy, lifetime and cost. This has enabled LEDs to become a realistic replacement of traditional light sources such as incandescent and fluorescent lamps.

5.6.1 Quality of LED Lighting

People have become used to high quality lighting provided by conventional light sources, especially those installed at home, such as incandescent and halogen lamps. Colour temperature, colour rendering index (CRI) and colour consistency are the main factors when evaluating the quality of a white light source.

The planckian black-body radiation spectrum is used as a standard for white light because its spectrum can be described using only one parameter, namely the colour temperature. The colour temperature (CT) or correlated colour temperature (CCT) of a white light source, given in units of Kelvin, is defined as the temperature of a planckian black-body radiator whose colour is closest to that of the white light source. With increasing temperatures, a planckian black-body radiator glows in the red, orange, yellowish white, white and ultimately bluish white. Therefore, the colour temperature of a white light source can be used to describe its appearance. For conventional lighting technologies, the CCT spans a wide range, from 2700 to 6500 K. ‘Warm white’ light, such as from incandescent lamps, has a lower colour temperature (2700–3500 K), while ‘cool white’, which is a more blue–white, has a higher colour temperature (3500–5500 K). ‘Warm white’ is in the most common lamp colour used in residential lighting in the USA and Europe.

Another important characteristic of a white light source concerns how precisely the different colours of an object show up under illumination from the light source. This is measured in terms of the CRI. Some examples of different light sources and their corresponding spectrum are shown in ■ Fig. 5.18. An ideal light source, such as sunlight, can reproduce colours perfectly and has a CRI of 100. Natural light LED lamps or full spectrum LED lamps, e.g. white LEDs based on near-UV LEDs plus RGB phosphors technology [107] have a CRI value as high as 95. Therefore the colours under full spectrum LED lamps also appear to be rich and vivid, similar to those under sunlight. ‘Warm white’ LEDs usually have a CRI higher than 80, which is acceptable to replace conventional light sources for most cases. While for conventional ‘cool white’ LEDs, the colour reproduction becomes insufficient, similar to fluorescent light.

It is noted that the current CIE colour rendition system of eight test colours to determine the CRI of a light source is designed around conventional light source technology and is not sufficient for LEDs. A new and better method of measuring and rating colour rendition for LED light sources is under development. For lighting professionals, the specific spectrum of a particular light source or the position of the colour points of a light source in relation to the black-body locus is a more accurate way of determining the value of the colour rendition.

Conventional light sources, such as incandescent and halogen lamps, have good colour consistency during their lifespan. For LED lighting, achieving good colour consistency is challenging. The colour distribution of blue LEDs and phosphors may result in greenish, blueish and pinkish white light. Furthermore, the colour of LEDs can shift with temperature and time. LED manufacturers have put a lot of efforts into understanding and controlling the colour shift of LEDs.

■ **Fig. 5.18** Examples of different light sources and their corresponding spectrum. A broader spectral source more accurately renders colours of illuminated objects Image from online resources

The uniformity of epitaxy, processing and phosphor technologies are improving continuously, enabling a tighter distribution of LEDs in the production process. The LED industry has also adopted a strict binning system to ensure colour consistency between LEDs. Meanwhile, LED industry standards and regulations are being developed. For example, in EU directive (EU-1194/2012), one of the functionality requirements is on colour consistency and a variation of chromaticity coordinates within a six-step MacAdam ellipse or less is required [87]. Some manufactures have implemented LED lighting products that fall within a single three-step MacAdam ellipse to avoid a difference in colour between two sources that may be perceived [74, 90].

Since LEDs have different colours at different temperatures, leading LED manufactures now specify their LEDs at real application temperatures (85 °C), instead of a 25 °C operating temperature, on their datasheet to ensure the customers receive the exact colour intended. Although the colour consistency of LED lighting has improved greatly, the colour shift during its long lifetime remains a large area of concern. The solutions rely on a better understanding of the degradation mechanisms of LED chips and other components with time. Considering the rapid improvement made during the short LED history so far, we have every reason to believe that within a short time LED lighting technology will totally surpass conventional light sources in both quantity and quality.

5.6.2 Efficacy

Radiometric units, such as optical power in watts (W), are used to characterise light in terms of physical quantities. However, the human eye is sensitive only to light in the visible spectrum, ranging from violet (with a wavelength of ~400 nm) through to red (with a wavelength of ~700 nm) and has different sensitivity at different wavelengths, as shown in ■ Fig. 5.19. The maximum sensitivity of the human eye is to green light with a wavelength of 555 nm. Therefore, to represent the light output of an optical source as perceived by the human eye, photometric

Fig. 5.19 Eye sensitivity function $V(\lambda)$ and luminous efficacy in lm/W. The maximum sensitivity of the human eye is to green light with a wavelength of 555 nm (Data after 1978 CIE [81]). It is noted that definition of the luminous efficacy here is the light power output in lumen divided by the optical power in (measured in W), rather than electrical power in

units, such as lumens (lm), are used instead of radiometric units. The efficacy of a light source takes into account the sensitivity of human vision, so that green light contributes more strongly to efficacy than blue or red light, and ultraviolet and infrared wavelengths do not contribute at all. The unit of efficacy is lumens per watt (lm/W), corresponding to light output power (as perceived by the human eye and measured in lumens) relative to electrical input power (measured in Watts).

It should be noted that there is a fundamental trade-off between efficacy and colour rendering [75]. The corresponding colour temperature should also be considered when comparing the efficacy of different white light sources. Generally speaking, a ‘warm white’ LED source of high CRI usually has lower efficacy compared with a ‘cool white’ LED source of lower CRI. The highest reported efficacy so far from a packaged LED device is 303 lm/W at a drive current of 350 mA and with a correlated colour temperature of 5150 K [76].

5.6.3 Lifetime

One of the main advantages of LED lighting is its long lifetime that potentially can span to 50,000 h or even 100,000 h. Similar to all electric light sources, LED lighting experiences a decrease in the amount of light emitted over time, a process known as lumen depreciation. For general lighting purpose, the useful life of an LED is defined as the point at which light output has declined to 70 % of initial lumens. The primary cause of LED lumen depreciation is heat generated at the LED junction that will affect the performance of key LED package components as

well as materials [77]. Heat management is therefore an important factor in determining the effective useful life of the LED. The lifespan of commercial LED replacement lamps is already longer than 15,000 h (some are longer than 25,000 h). As LEDs become more efficient over time, the problem of heat management will largely disappear and a longer lifetime of LED lighting is expected. The lifetime of LED lamps is also limited by the shorter lifetime of the control electronics used. So more attention is being paid to the development of sophisticated control electronics for LED lighting.

5.6.4 Cost

Cost is probably the major factor limiting the widespread use of white LEDs in our homes and offices. GaN-based LED replacement lamps are significantly more expensive than filament light bulbs or compact fluorescent lamps (CFLs). However, the cost per lumen is continuously decreasing, following the Haltz's law (see Fig. 5.20).

It should be noted that the total ownership cost of lighting includes energy savings and replacement cost, which makes LEDs more competitive, compared to conventional lighting technologies. Nevertheless, in order to achieve significant market penetration, the initial cost (\$/klm) of LEDs needs to be reduced 10 times to be comparable to the cost of CFLs. To achieve the required cost reduction, many aspects of the manufacturing process will need to be addressed in parallel, as illustrated in Fig. 5.21. This diagram shows that the cost reduction shouldn't be based on sacrificing the three main LED quality factors: efficiency, reliability and customer experience. To make sure LED lighting remains a high quality light source, many aspects including LED materials, chip design, white light generation, component design, power supply circuit, luminaire optical and thermal design need to be taken care of.

Fig. 5.20 Haltz's law showing that every decade, the cost per lumen falls by a factor of 10, and the amount of light generated per LED package increases by a factor of 20

■ Fig. 5.21 Integrated systems approach to solid-state-lighting manufacturing (after Mark McClear, Cree, Inc., SSL manufacturing workshop, Vancouver, OR, June 2009)

5.7 LED Lighting Applications: The Present and Future

Although significant improvements are still expected, the present performance of nitride LEDs is nevertheless superior in many respects compared with conventional lighting. LEDs are compact, efficient, long-lasting and controllable, and are already widely used, for example (as shown in ■ Fig. 5.22), as traffic signals, in large outdoor displays, as interior and exterior lighting in aircraft, cars and buses, as bulbs in flash lights and as backlighting for LCD TVs cell phones and displays. Due to their long lifetime, LEDs are also being fitted on airport runways, where the operational cost can be significantly lowered: traditional lighting on runways lasts for about 6 months, and the runway has to be closed to replace it, at considerable cost. The performance of LEDs improves at lower temperatures, which is perfect for illuminating refrigerated displays in supermarkets, where CFLs give poor performance because their efficiency is very low when cold. Architectural lighting also favours LEDs, which combine art due to the flexibility in use of LEDs, with energy saving and eco-friendliness.

The research and applications of LED lighting in the horticultural industry (■ Fig. 5.23) have also attracted a lot of attention [108], with benefits including better control of plant growth, increased yield, earlier flowering, faster root growth and more economical use of space. The lower electricity consumption and controllable light spectrum design are especially attractive features of LED lighting for horticulture applications.

Optogenetics is a new area of neuroscience that uses light to stimulate targeted neural pathways in the brain to uncover how neurons communicate and give rise to more complex brain functions. One key technical challenge in optogenetics is the realisation of a reliable implantable tool to precisely deliver light to the targeted neurons and to simultaneously record the electrical signals from the individual neuron. Such a neural probe requires the successful integration of light sources, detectors, sensors and other components on to an ultrathin cellular-scale injection needle, which can be inserted deep into the brain with minimum damage of tissue. Micro-LEDs are an ideal light source for this application due to the small size and controllable emission wavelength.

■ Fig. 5.22 Various application examples of LEDs as retail light, as backlighting for LCD TVs, as outdoor street light, as bicycle light, as exterior lighting in cars, as architectural lighting and as airport runway light. Images from Osram, with permission

■ Fig. 5.23 Philips LED lighting for fast-track growth in horticulture. Image from Philips, with permission

Visible light communication (VLC) technology, more recently referred to as Li-Fi (Light Fidelity), transmits data using light sources that modulate intensity faster than the human eye can perceive. Although still in its infancy, VLC is believed to be a future technology in wireless communication. LEDs are especially suitable for this application due to their fast switch on/off rate and long lifetime. By using an array of micro-LEDs, instead of conventional LEDs, the data transmit rate can be increased to more than 10 Gbps (Gigabits per second). An even bigger picture of this technology is to combine information displays, lighting and

■ **Table 5.2** Comparison of LED light bulbs with conventional classic light bulbs

	Incandescent	Halogen incandescent	Compact florescent	LED light bulbs

Lumen	1100	1200	970	1055
Power (W)	75	70	15	13
Efficacy (lm/W)	15	17	65	81
Colour temperature (K)	2700	2800	2700	2700
Colour rendering index	100	100	81	80
Rated lifetime (h)	750–2000	2000	10,000	15,000
Mercury content (mg)	0	0	≤2	0
Warm-up time to 60 % light	Instant full light	Instant full light	5–40 s	Instant full light
Sales price	Banned [109]	£2.00	£5.00	£10.00

high-bandwidth communications in a single system, which will bring revolutionary solutions for machine-to-machine communications, smart homes and vehicles, mobile communications, imaging systems, personal security, healthcare and so on.

5.7.1 General Illumination and Energy Saving

Among all these exciting applications of LED lighting, those in general illumination, including residential, office, shop, hospitality, industrial, outdoor and architectural lighting, are the most relevant to our daily life and have the greatest energy saving potential. Both LED replacement classic light bulbs and LED fixtures are used for general illumination. A comparison of indoor LED light bulbs with other conventional light bulbs is given in ■ Table 5.2, showing the advantages of LED lighting in energy saving without sacrificing performance. Due to its high initial cost, the current market penetration of LED lighting products is still very small. However, if the current trends in LED price and performance continue, LED lighting is projected to gain significant market penetration in USA, reaching 48 % of lumen-hour sales of the general illumination market by 2020, and 84 % by 2030.

Global population growth and urbanisation are increasing the overall demand for lighting products and the corresponding energy consumption by lighting. According to a recent US Department of Energy (DOE) report, lighting consumed ~18 % of total US electricity use in 2013, using approximately 609 TWh of electricity, or about 6.9 quads of source energy. LEDs are projected to reduce lighting energy consumption by 15 % in 2020 and by 40 % in 2030, saving 3.0 quads in 2030 alone. Assuming the current mix of generation power stations, these energy savings would reduce green house gas emission by approximately 180 million metric tons of carbon dioxide. Considering the global population growth, resource scarcity and climate change concerns, the development and adoption of LED technology is strategically important for a sustainable society.

■ **Fig. 5.24** Some features of the human circadian (24-h) biological clock. Image was done by Yassine Mrabet and uploaded by Addicted04 to Wikipedia, under creative CC BY-SA 3.0 free license

5.7.2 Circadian Rhythm Lighting

LED-based solid-state lighting is not just a replacement of traditional illuminations, but rather a multifunctional device we can use to improve our mood, health, productivity and much more. Because it is easily colour-tunable and dimmable, LED lighting is ideal to create circadian rhythm lighting that matches the needs of human biological cycles, or circadian rhythms, in the most effective and appropriate way.

Human beings are governed to some degree by an internal biological clock, called the circadian rhythm, as illustrated in ■ Fig. 5.24. Light is the most powerful stimulus of the human body clock, and the timing of light exposure during the course of a day is responsible for how circadian rhythms are synchronised with the environment. For example, one of the best cures of ‘jet lag’ caused by circadian rhythm disruption is exposure to daylight to reset the body clock.

Modern industrialised society heavily relies on artificial lighting. Research tells us that circadian rhythm disruption through inappropriate artificial light causes many physical and mental health issues: fatigue, cancer, obesity, diabetes, depression, mood and sleep disorders, reduced physical and mental performance, reduced productivity and irritability are all related in some shape or form to a circadian system that isn’t functioning properly. The most natural light is sunlight, which is dynamic and variable in brightness, colour temperature and spectral distribution during the day. Daylight provides bright blue-rich light in the early morning to deliver an alerting signal as we wake up and a warm, low-level light in the early evening to prepare our body to rest.

The dynamic features and spectral design flexibility of LED lighting enable the creation of personalised lighting to mitigate circadian rhythm disruption, optimise mood and visual experience, and improve our sense of wellbeing, in better ways than ever before. Combined with smart building control systems, LED circadian

rhythm lighting can be programmed to change colour temperature and light level automatically, allowing for the indoor reproduction of natural outdoor lighting conditions. Some circadian rhythm lighting products are already commercially available, for example, on aircraft for long-haul flights. In the future, we could expect LED lighting to become more intelligent and closer to natural light, contributing strongly to our health and wellbeing, as well as energy saving.

5.8 Chapter Summary

LED-based solid-state lighting promises to provide a high quality and energy efficient light source for our daily life. With continuous advances in efficiency and reductions in cost, LED lighting is on course to be the dominant form of lighting in homes, offices, cities and transport throughout the world. LED lighting is more than an energy efficient alternative to conventional light sources; it is suitable to create circadian rhythm lighting that can make us healthier and more productive. LED lighting is also intelligent and could interface with building management systems, transmit high-speed wireless data, fine-tune occupancy and functional sensing, and is an important integral part of our future smart home.

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