

Solid-State Lighting Based on Light Emitting Diode Technology

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- 5.1 Historical Development of LEDs – 88**
- 5.2 The Importance of Nitride Materials – 89**
- 5.3 LED Basics – 90**
- 5.4 Fabrication of an LED Luminaire – 92**
 - 5.4.1 Efficiency and Efficacy – 93
- 5.5 Research Challenges – 94**
 - 5.5.1 Crystal Growth – 95
 - 5.5.2 Internal Electric Field – 97
 - 5.5.3 *p*-Type Doping – 99
 - 5.5.4 Green Gap and Efficiency Droop – 100
 - 5.5.5 Chip Design – 102
 - 5.5.6 Generation of White Light with LEDs – 103
 - 5.5.7 LED Packaging – 105
- 5.6 LEDs for Lighting – 106**
 - 5.6.1 Quality of LED Lighting – 106
 - 5.6.2 Efficacy – 107
 - 5.6.3 Lifetime – 108
 - 5.6.4 Cost – 109
- 5.7 LED Lighting Applications: The Present and Future – 110**
 - 5.7.1 General Illumination and Energy Saving – 112
 - 5.7.2 Circadian Rhythm Lighting – 113
- 5.8 Chapter Summary – 114**
- References – 114**

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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-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

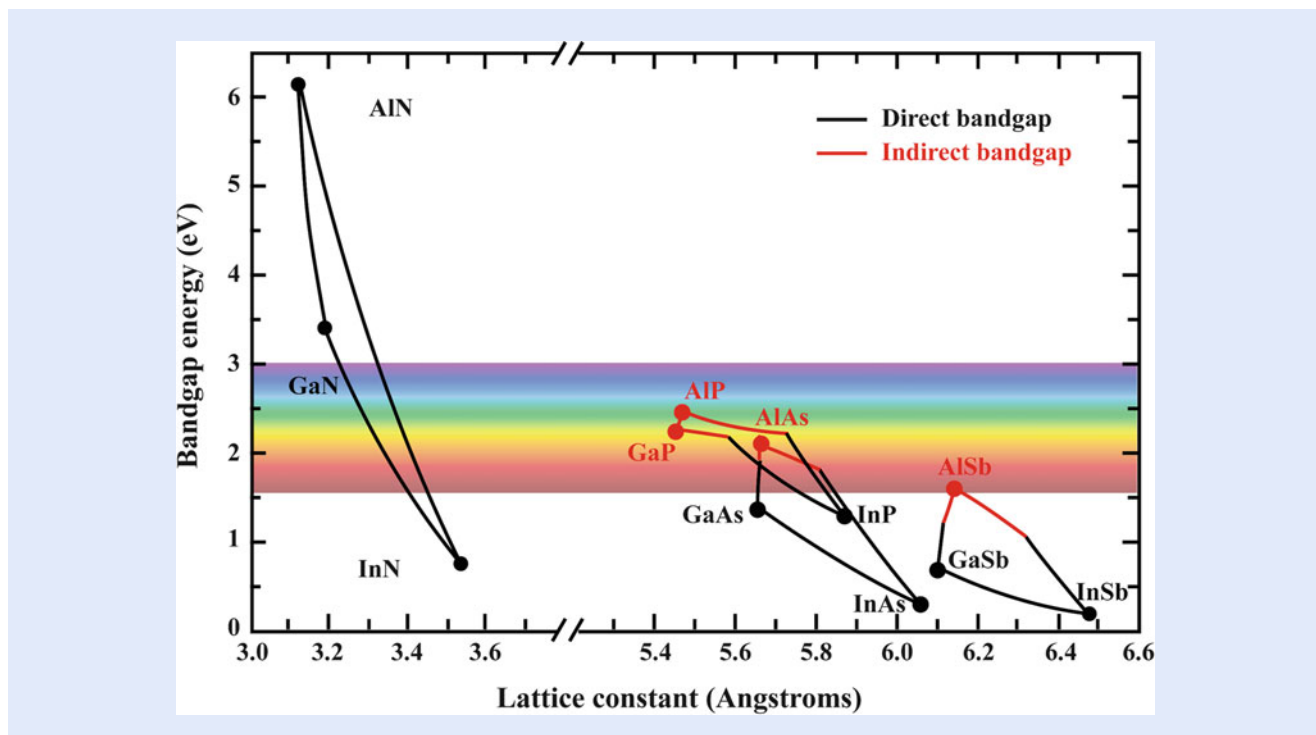


Fig. 5.1 Bandgap energies at 300 K of III-V compound semiconductors, plotted from data given in Vurgaftman et al. [4] and Vurgaftman and Meyer [5]. For the nitrides, the hexagonal a lattice constant has been used. The energy range corresponding to the visible spectrum is also indicated

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].

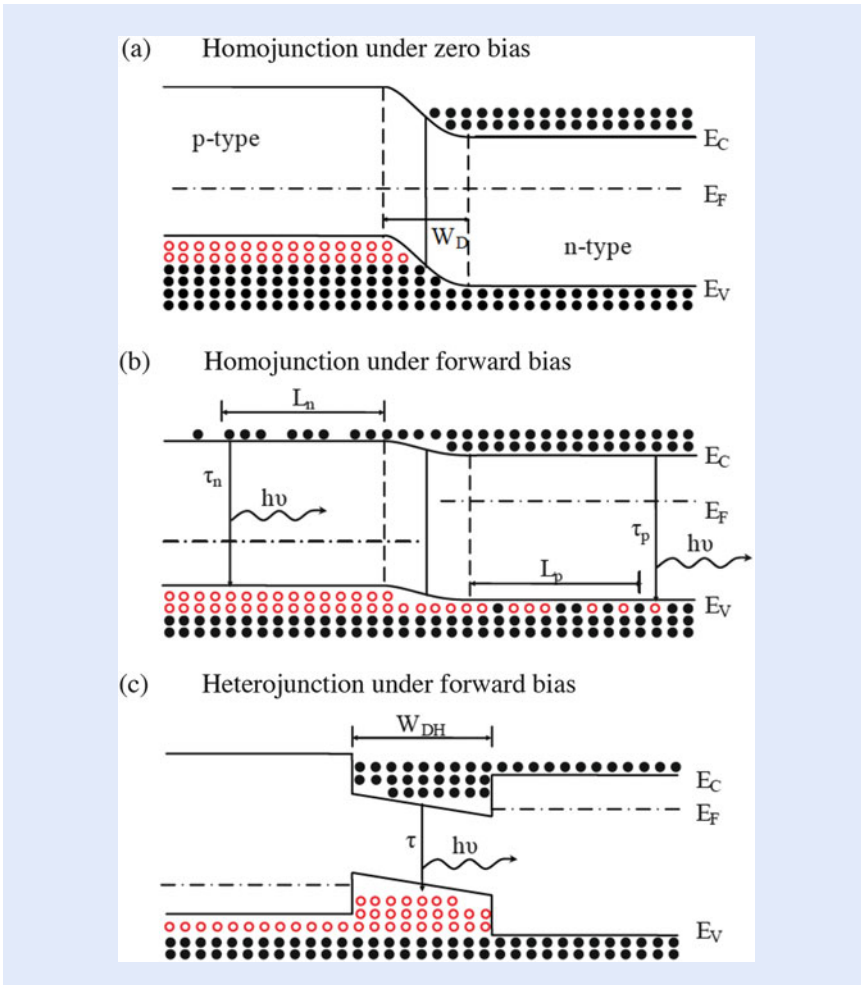
AlGaN/GaN heterostructures are also suitable for electronic devices such as high electron mobility transistors (HEMTs), which have applications in microwave and radio frequency power amplifiers used for communications technology [9]. Such a wide bandgap materials system also allows device operation at 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.

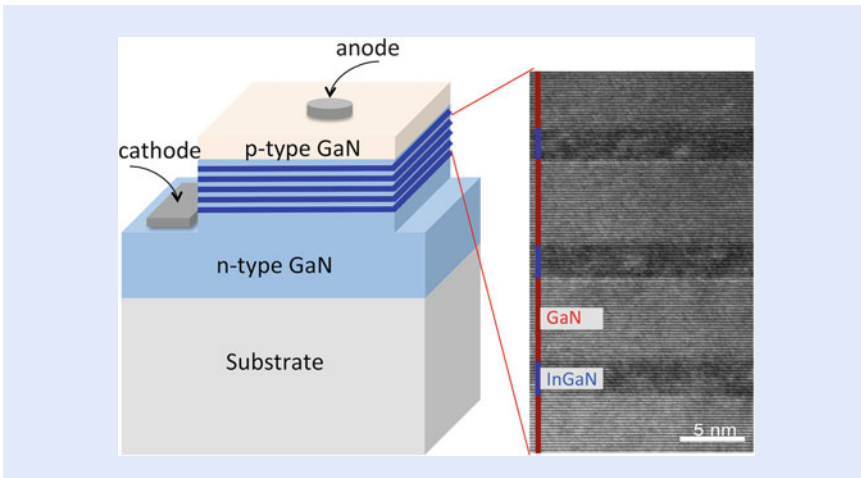
5.3 LED Basics

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

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