Current Science Research Bulletin
Volume 03 (10), October 2026, pp. 228-235
CrossRef DOI: 10.55677/csrb/02-V03I10Y2026
Available on: https://csrbjournal.org/
e-ISSN: 3050-7103
p-ISSN: 3050-709X

LED Technology: Evolution and Applications

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ABSTRACT: Light-emitting diodes (LEDs) have revolutionized modern lighting and optoelectronic technologies owing to their high energy efficiency, long operational lifetime, and versatile applications. This review provides an overview of the historical development of LED technology, from the discovery of electroluminescence to the emergence of high-efficiency blue and white LEDs and advanced Micro-LED systems. The fundamental physical principles of light emission, semiconductor materials, and technological advances are discussed, with particular emphasis on GaN-based heterostructures and quantum-well engineering. Major applications in solid-state lighting, display technologies, optical communications, agriculture, and biomedical systems are highlighted. Furthermore, current challenges related to quantum efficiency, material defects, thermal management, and device miniaturization are examined. Future research directions involving perovskites, quantum dots, two-dimensional semiconductors, and first-principles computational approaches are also outlined. This review provides a concise perspective on the technological evolution and future development of high-performance LED devices.

KEYWORDS: Light-emitting diodes, Semiconductor materials, GaN, Micro-LED, Optoelectronics.

1. INTRODUCTION

Light-emitting diodes (LEDs) represent one of the most significant technological advances in semiconductor physics and modern optoelectronics. An LED is a semiconductor device that directly converts electrical energy into optical radiation through the radiative recombination of electrons and holes within a p–n junction or an appropriately engineered semiconductor heterostructure [1,2]. Compared with conventional lighting technologies, such as incandescent and fluorescent lamps, LEDs offer several distinct advantages, including high energy efficiency, long operational lifetime, compact size, flexible optical and electrical control, and rapid switching response [2–4]. These characteristics have established LEDs as essential components in a broad range of applications, including solid-state lighting, electronic displays, optical communication systems, biomedical devices, horticultural lighting, and various industrial technologies [3–6]. The evolution of LED technology has been closely associated with major advances in solid-state physics, materials science, semiconductor fabrication, and nanoscale engineering. From the early observations of relatively weak electroluminescence in semiconductor materials during the twentieth century, LED technology has progressed toward highly efficient light-emitting devices capable of operating across a broad spectral range, extending from the ultraviolet to the infrared regions [1,2]

2. HISTORICAL DEVELOPMENT AND TECHNOLOGICAL EVOLUTION OF LIGHT-EMITTING DIODES

The development of light-emitting diode (LED) technology has undergone several transformative stages, driven by advances in semiconductor physics, crystal growth techniques, materials engineering, and optoelectronic device fabrication. From the initial discovery of electroluminescence in semiconductor crystals to the emergence of highly efficient blue and white LEDs, each technological milestone has contributed to improving emission efficiency, spectral tunability, operational reliability, and practical applicability.

The historical evolution of LED technology can be broadly divided into six major stages, as summarized in Table 1.

Cite the Article: *Hao, M.T., Tung, N.T. (2026). LED Technology: Evolution and Applications. Current Science Research Bulletin, 3(10), 228-235. https://doi.org/10.55677/csrb/02-V03I10Y2026*

Publication Date: *October 20, 2026*

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Table 1. Major milestones in the historical development of LED technology.

Period	Major technological developments	Scientific and technological significance
1907–1961 [6]	Discovery of semiconductor electroluminescence and early investigations of light-emitting materials	Establishment of the physical foundations of semiconductor light emission
1962–1971 [7]	Development of the first practical visible red LEDs and subsequent progress in red, orange, yellow, and green emission	Emergence of LEDs as commercially viable optoelectronic devices
1972–1992	Improvements in luminous efficiency, semiconductor heterostructures, and high-brightness LED technology	Expansion of applications in electronic displays, signaling, and instrumentation
1993–2000 [8]	Breakthroughs in high-efficiency blue LEDs based on GaN/InGaN and development of phosphor-converted white LEDs	Establishment of the technological foundation for energy-efficient white solid-state lighting
2000–2015	Commercialization of high-power LEDs, advances in quantum-well structures, thermal management, and light extraction	Large-scale adoption of LED technology in general illumination and industrial applications
2015–present [9-11]	Development of Mini-LEDs, Micro-LEDs, UV-LEDs, quantum-dot LEDs, intelligent lighting, and emerging nanoscale emitters	Expansion toward next-generation displays, integrated photonics, advanced sensing, and multifunctional optoelectronic systems

These developmental stages reflect a transition from basic investigations of electroluminescence to sophisticated semiconductor devices whose optical, electronic, and thermal characteristics can be engineered at the micro- and nanoscale. In particular, progress in III–V compound semiconductors, heterostructure design, and quantum confinement has played a central role in enhancing radiative recombination efficiency and extending the accessible emission spectrum. Although these periods provide a useful chronological framework, technological developments frequently overlap. For example, research on blue-emitting semiconductor materials began well before the commercial success of high-brightness GaN-based LEDs in the 1990s, while several modern display technologies originated from earlier advances in LED miniaturization and semiconductor processing.

2.1. Discovery of Electroluminescence and Establishment of Scientific Foundations (1907–1961)

In 1907, the British scientist Henry Joseph Round observed light emission from silicon carbide (SiC) crystals under an applied electrical potential. This observation is considered one of the earliest reports of electroluminescence in semiconductor materials [12]. In 1927, Oleg Losev published investigations on light emission from semiconductor structures and proposed the potential application of this phenomenon in electrically driven light sources [12,13]. However, limitations in semiconductor materials and fabrication technologies prevented these early discoveries from being commercially exploited. Over the following decades, advances in electronic band theory, the understanding of p-type and n-type semiconductors, and the development of p–n junction fabrication techniques established the foundations of modern LED technology [12]. Scientific significance: This period established the physical basis of semiconductor electroluminescence and opened new avenues for the direct conversion of electrical energy into optical radiation.

2.2. Emergence of Visible Light-Emitting Diodes (1962–1971)

In 1962, Nick Holonyak Jr. and S. F. Bevacqua at General Electric developed a practical visible red light-emitting diode based on gallium arsenide phosphide (GaAsP) [14]. This achievement represented a major milestone in the development of modern visible LED technology. In subsequent years, research focused on improving emission intensity, operational stability, and spectral coverage. Semiconductor materials such as GaAs, GaP, and GaAsP were investigated for light-emitting devices, with GaAs primarily used for infrared emission and GaP- and GaAsP-based structures enabling visible emission in the red, orange, yellow, and green spectral regions [12,15]. Early-generation LEDs exhibited relatively low luminous efficiency and limited brightness, restricting their applications mainly to indicator lamps, numerical displays, and electronic devices. Technological significance: This period marked the transition of LED technology from laboratory research to the practical development and commercialization of semiconductor optoelectronic devices.

2.3. Improvements in Efficiency and Expansion of the Emission Spectrum (1972–1992)

During this period, advances in epitaxial growth techniques and compound semiconductor materials significantly improved the luminous efficiency of LEDs [16,17]. One of the major research directions involved the development of semiconductor

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heterostructures, in which materials with different band gaps were combined to enhance carrier confinement and increase the probability of radiative recombination [17]. Semiconductor materials such as AlGaAs, GaP, GaAsP, and subsequently AlGaInP played important roles in the development of high-brightness LEDs, particularly in the red-to-yellow spectral region [16,18]. Furthermore, improvements in crystal growth, doping techniques, and defect control enhanced device quality and reduced energy losses associated with nonradiative recombination. Consequently, LEDs became increasingly widespread in electronic displays, measurement instruments, traffic signaling systems, and industrial control applications [16].

2.4. Breakthroughs in Blue and White Light-Emitting Diodes (1993–2000)

This period represented a major turning point in the development of LED lighting technology.

In the early 1990s, Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura made groundbreaking contributions to the development of high-efficiency blue LEDs based on gallium nitride (GaN) and related semiconductor compounds [19,20]. These achievements addressed major challenges associated with GaN crystal growth, p-type doping, and the fabrication of efficient light-emitting heterostructures [19,20]. The development of high-brightness blue LEDs enabled the realization of white LEDs, particularly through the combination of blue-emitting semiconductor chips with wavelength-converting phosphor materials [21]. In 2014, the Nobel Prize in Physics was awarded to Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura for the invention of efficient blue LEDs, which enabled the development of energy-saving white light sources [21].

Scientific and societal significance: LED technology evolved beyond conventional display and signaling applications, establishing the foundation for modern solid-state lighting systems [16, 20].

2.5. Development of High-Power LEDs and Commercialization of Solid-State Lighting (2000–2015)

Since the beginning of the twenty-first century, research has increasingly focused on improving the quantum efficiency, luminous efficacy, output power, and thermal management of light-emitting diodes (LEDs) [22,23]. Quantum-well (QW) and multiple-quantum-well (MQW) structures based on InGaN/GaN have been widely employed to enhance electron and hole confinement within the active region, thereby improving radiative recombination efficiency [23,24]. Meanwhile, advances in electrode design, transparent conductive layers, surface texturing, and packaging technologies have contributed to improved light-extraction efficiency and overall device performance [22,23]. As a result, LEDs have progressively replaced conventional light sources in residential, commercial, industrial, transportation, and architectural lighting applications [22]. One of the major scientific challenges investigated during this period was the efficiency droop phenomenon, characterized by a reduction in external quantum efficiency at high injection current densities. This issue stimulated extensive research into Auger recombination, carrier leakage, internal electric fields, and other carrier-loss mechanisms in LED heterostructures [24,25].

2.6. Next-Generation LEDs and Advanced Optoelectronic Technologies (2015–Present)

In recent years, LED research has expanded toward improving energy efficiency and developing micro- and nanoscale light-emitting structures with enhanced optical and electronic functionalities [26,27]. Mini-LED technology employs miniaturized LEDs as backlighting sources, enabling a greater number of local dimming zones and consequently improving display contrast, brightness control, and overall image quality [26]. Micro-LED technology utilizes micrometer-scale, self-emissive LED elements as individual display pixels, offering high brightness, rapid response times, long operational lifetimes, and potential improvements in energy efficiency [26,27]. Ultraviolet LEDs (UV-LEDs), particularly those based on AlGaN semiconductor alloys, have attracted considerable attention for applications in disinfection, chemical analysis, photochemical processes, and biomedical technologies [28]. Quantum-dot light-emitting diodes (QLEDs) exploit the size-dependent optical properties of semiconductor quantum dots to achieve high color purity, tunable emission wavelengths, and improved display performance [29]. Furthermore, current research increasingly explores perovskite-based LEDs, two-dimensional semiconductor emitters, nanostructured light sources

3. PHYSICAL PRINCIPLES AND SEMICONDUCTOR MATERIALS USED IN LIGHT-EMITTING DIODES

3.1. Light-Emission Mechanism

When a light-emitting diode (LED) is forward-biased, electrons from the n-type semiconductor region and holes from the p-type region are injected into the active region. Radiative recombination of these charge carriers results in the emission of photons, converting electrical energy directly into optical radiation [30,31].

The energy of an emitted photon is expressed as

$$\varepsilon(eV) = \frac{hc}{\lambda(m)}$$

where h is Planck's constant, c is the speed of light in vacuum, ν is the photon frequency, and λ is the corresponding wavelength in vacuum. For optical transitions occurring near the semiconductor band edges, the emission wavelength can be approximately estimated using

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$$\lambda(m) = \frac{1240}{E_g(eV)}$$

where Eg represents the semiconductor band-gap energy (eV)

This relationship indicates that the band-gap energy plays a fundamental role in determining the spectral characteristics of LED emission. However, the actual emission wavelength also depends on the electronic band structure, quantum confinement effects, excitonic states, and other material-dependent factors [30, 32].

3.2. Representative Semiconductor Materials for LED Applications

Various semiconductor materials have been developed to achieve efficient light emission across different spectral regions. The selection of suitable materials is primarily determined by their electronic band structures, band-gap energies, radiative recombination characteristics, and compatibility with semiconductor fabrication technologies [30,31,33].

Table 2. Representative semiconductor materials and their principal applications in LED technology.

Semiconductor material	Principal emission region	Key characteristics and applications
GaAs	Infrared	Direct-band-gap semiconductor with efficient radiative recombination
GaAsP	Red, orange, and yellow	Widely employed in early generations of visible LEDs
AlGaInP	Red to yellow	High-brightness and high-efficiency visible LEDs
GaN	Violet and near-ultraviolet	Wide-band-gap semiconductor forming the foundation of nitride-based LEDs
InGaN/GaN	Blue and green	High-power LEDs and phosphor-converted white-light sources
AlGaN	Ultraviolet	UV-LEDs for disinfection, sensing, and photochemical applications
Semiconductor quantum dots	Tunable visible emission	Size- and composition-dependent emission for quantum-dot LEDs and advanced displays

The selection of semiconductor materials for LED fabrication depends on several fundamental parameters, including band-gap energy, direct or indirect band-gap characteristics, doping capability, crystalline quality, and radiative recombination efficiency [31, 34]. In particular, direct-band-gap semiconductors are generally preferred for efficient light emission because electron–hole recombination can occur without requiring phonon-assisted momentum conservation. Furthermore, advances in alloy engineering, heterostructure design, and quantum confinement have enabled precise control of emission wavelengths and improved the performance of modern LED devices [31,33,34].

4. APPLICATIONS OF LIGHT-EMITTING DIODES

4.1. Residential and Industrial Lighting

Light-emitting diodes (LEDs) are widely employed in residential buildings, educational institutions, hospitals, manufacturing facilities, street lighting, and architectural illumination. Their major advantages include high energy efficiency, long operational lifetimes, and flexible brightness control, making them an increasingly important alternative to conventional lighting technologies [35,36].

4.2. Display Technologies

LEDs are extensively used in advertising billboards, outdoor displays, liquid crystal display (LCD) backlighting, and self-emissive Micro-LED displays. These technologies enable high-resolution imaging, enhanced contrast ratios, and accurate color reproduction, contributing to the continuous advancement of modern display systems [37,38].

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4.3. Advanced Agricultural Applications

LED technology enables precise control of the spectral composition and intensity of illumination, thereby influencing photosynthetic activity, plant growth, and developmental processes. Representative applications include greenhouse cultivation, vertical farming, and controlled-environment agriculture, where optimized lighting conditions can improve crop productivity and resource-use efficiency [39,40].

4.4. Biomedical and Healthcare Applications

LEDs are increasingly utilized in phototherapy devices, biomedical monitoring systems, optical sensors, and light-based therapeutic treatments. Their effectiveness depends on several parameters, including emission wavelength, optical power, irradiation duration, and delivered light dose. These characteristics make LEDs promising light sources for noninvasive diagnostic and therapeutic applications [41].

4.5. Optical Communication Systems

Owing to their rapid switching response and capability for high-speed intensity modulation, LEDs can be employed in visible light communication (VLC), light fidelity (Li-Fi), and short-range optical wireless communication systems. These technologies enable the simultaneous use of visible light for illumination and data transmission, offering potential advantages in communication capacity and electromagnetic compatibility [42].

4.6. Transportation and Automotive Applications

LEDs are widely integrated into automotive headlights, signaling lamps, taillights, dashboard displays, and adaptive lighting systems. In particular, matrix LED technology enables spatially selective control of light distribution, improving road visibility and reducing glare for other road users [36,43].

5. CURRENT CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite substantial technological progress, several scientific and engineering challenges remain in the development of next-generation LED technologies. Improving quantum efficiency: Further improvements require the suppression of nonradiative recombination, Auger-related carrier losses, and carrier leakage, particularly under high-current-density operating conditions [44]. Controlling material quality: Reducing crystalline defects, lattice strain, and electronic trap states remains essential for enhancing radiative recombination efficiency and device reliability. Optimizing thermal management: Advanced heat-dissipation strategies are necessary to minimize junction-temperature increases and maintain the optical performance and operational stability of high-power LEDs [36]. Developing emerging semiconductor materials: Perovskites, semiconductor quantum dots, two-dimensional materials, and nanoscale heterostructures offer promising opportunities for wavelength tunability, enhanced light emission, and multifunctional optoelectronic applications [38,45,46]. Miniaturizing device architectures: Micro-LED technologies require further improvements in emission efficiency, mass-transfer processes, pixel integration, and large-scale manufacturing to achieve commercially viable high-resolution displays [39,40]. Enhancing stability and sustainability: Extending device lifetimes, reducing the use of environmentally hazardous materials, and improving recyclability are important considerations for the sustainable development of LED technologies. In particular, first-principles computational approaches, including density functional theory (DFT), provide valuable insights into the electronic structures, band-gap characteristics, defect states, optical properties, and doping effects of emerging semiconductor materials. However, accurate descriptions of optical excitation spectra and electron–hole recombination processes often require theoretical approaches beyond ground-state DFT, such as many-body perturbation theory within the GW approximation, the Bethe–Salpeter equation (BSE), and carrier-dynamics models [47,48]. These computational methods, combined with experimental investigations, can contribute to the rational design and optimization of next-generation light-emitting materials and devices.

6. CURRENT CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite significant advances in light-emitting diode (LED) technology, several scientific and technological challenges remain to be addressed to further improve device performance, reliability, and sustainability.

Improving quantum efficiency: Suppressing nonradiative recombination mechanisms, Auger recombination losses, and carrier leakage remains essential for enhancing the quantum efficiency of LEDs, particularly under high-current-density operating conditions [49,50]. Controlling material quality: Reducing crystalline defects, lattice strain, and electronic trap states is critical for improving radiative recombination efficiency and minimizing energy losses in semiconductor light-emitting structures [51]. Optimizing thermal management: Developing effective heat-dissipation strategies is necessary to maintain high luminous efficiency, operational stability, and long-term reliability in high-power LED devices [52]. Developing emerging semiconductor materials: Perovskites, semiconductor quantum dots, two-dimensional materials, and nanoscale heterostructures offer promising opportunities for wavelength tunability, enhanced optical properties, and next-generation optoelectronic applications [53,54]. Miniaturizing

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device architectures: Further development of Micro-LED technology requires improvements in emission efficiency, mass-transfer techniques, device integration, and large-scale manufacturing processes to enable high-resolution and energy-efficient displays [55]. Enhancing stability and sustainability: Extending operational lifetimes, reducing the use of environmentally hazardous materials, and improving recyclability are important priorities for the sustainable development of LED technologies. In particular, first-principles computational approaches, such as density functional theory (DFT), provide valuable insights into the electronic structures, band-gap characteristics, defect states, optical properties, and doping effects of emerging semiconductor materials. However, accurate descriptions of optical excitation spectra and electron–hole interactions generally require theoretical methods beyond ground-state DFT, including the GW approximation, the Bethe–Salpeter equation (BSE), and carrier-dynamics models [56,57]. Integrating advanced computational simulations with experimental investigations is therefore expected to facilitate the rational design and optimization of high-performance light-emitting materials and devices.

7. CONCLUSIONS

The historical development of LED technology reflects continuous progress in semiconductor physics and materials science, from the initial discovery of electroluminescence to the realization of highly efficient semiconductor light sources. In particular, the development of GaN/InGaN-based blue LEDs represented a major technological breakthrough, enabling the widespread implementation of white LEDs and energy-efficient solid-state lighting systems [58]. Currently, LEDs have evolved beyond conventional illumination sources to become essential components in advanced display technologies, optical communication systems, sensing platforms, biomedical devices, and smart agricultural applications. Continued advances in nanostructured materials, semiconductor heterostructures, and microelectronic fabrication technologies are expected to further enhance the efficiency, stability, and functional versatility of LED devices, expanding their potential applications in next-generation optoelectronic systems.

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