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LEDs: The new revolution in lighting / Les LED : La nouvelle révolution de l'éclairage

Invention, development, and status of the blue light-emitting diode, the enabler of solid-state lighting

L'invention, le développement et l'état de l'art des diodes électroluminescentes à lumière bleue, bases de l'éclairage à l'état solide

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A B S T R A C T

The realization of the first high-brightness blue-light-emitting diodes (LEDs) in 1993 sparked a more than twenty-year period of intensive research to improve their efficiency. Solutions to critical challenges related to material quality, light extraction, and internal quantum efficiency have now enabled highly efficient blue LEDs that are used to generate white light in solid-state lighting systems that surpass the efficiency of conventional incandescent lighting by 15–20×. Here we discuss the initial invention of blue LEDs, historical developments that led to their current state-of-the-art performance, and potential future directions for blue LEDs and solid-state lighting.

R É S U M É

La mise au point des premières diodes électroluminescentes (LED) bleues en 1993 a marqué le début de plus de vingt années de recherches intensives dans le but d'améliorer leur efficacité. Les solutions qui ont été apportées à des défis critiques associés à la qualité des matériaux, à l'extraction de la lumière et au rendement quantique interne permettent à présent de disposer de LED bleues hautement performantes utilisables pour générer de la lumière blanche dans des systèmes d'éclairage à l'état solide qui surpassent en efficacité les ampoules à incandescence d'un facteur de 15 à 20×. Nous évoquons ici les prémices de l'invention des LED à lumière bleue, l'histoire des développements qui ont mené à la performance de l'état de l'art actuel, ainsi que de potentielles futures directions de recherche en matière de LED à lumière bleue et d'éclairage à l'état solide.

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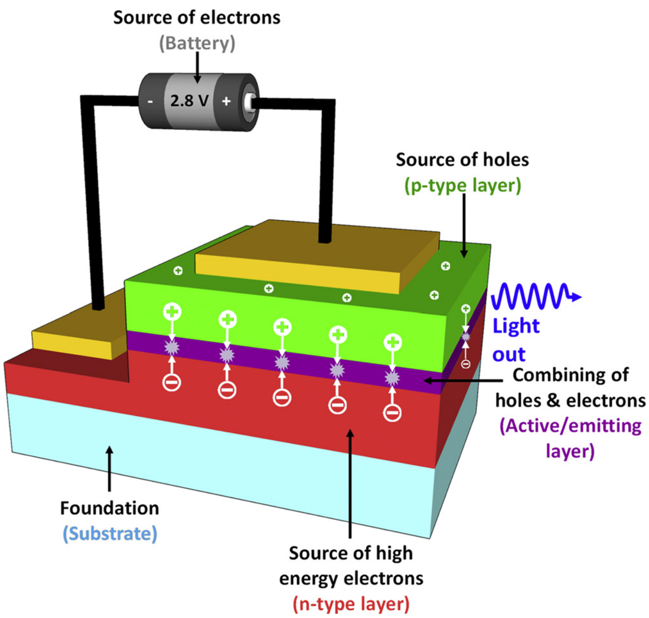

Fig. 1. Schematic of a simple double heterostructure LED, showing the basic operation, substrate, epitaxial layers, and recombination of electrons and holes in the active region to produce photons. Adapted from reference [9]. Copyright 2015 by John Wiley and Sons, Inc. Reprinted by permission of John Wiley and Sons, Inc.

1. Introduction

Lighting accounts for 15–22% of electricity consumption, depending upon the country, and solid-state lighting has the potential to provide enormous energy savings across the globe [1]. In the United States alone, the Department of Energy (DOE) conservatively predicts that solid-state lighting will save 261 terawatt-hours (TW h) annually, representing a 40% reduction in site electricity consumption relative to incumbent technologies such as incandescent and fluorescent [1]. A more aggressive forecast places the annual energy savings from solid-state lighting at 395 TW h by 2030 [1]. At the heart of solid-state lighting are high-brightness, high-efficiency GaN-based light-emitting diodes (LEDs), which represent the state-of-the-art in efficiency, reliability, form factor, and versatility for lighting and displays. The global LED lighting market in 2016 was estimated to be USD 26 billion [2] and commercial solid-state lighting products using GaN-based LEDs are now capable of providing >150 lm/W luminous efficacy and >50,000 hours operating lifetime. However, the development of such high performance LEDs was fraught with complex challenges. Although the first GaN growth was performed using hydride vapor phase epitaxy (HVPE) at RCA Laboratories in 1969 [3], GaN-based materials were not an obvious platform for reliable high-brightness LEDs due to a variety of inherent roadblocks. GaN-based materials initially lacked a native, lattice-matched substrate, leading to large strains and high dislocation densities; p-type doping did not exist; and piezoelectric effects made it challenging to design efficient active regions. With several decades of work, these challenges were largely overcome and Nakamura et al. demonstrated the first high-brightness GaN-based blue LEDs in 1993 [4]. This paper summarizes the historical developments associated with the invention of high-brightness blue LEDs, reviews their current performance, and discusses potential future directions for solid-state lighting. First, we review early breakthroughs that led to high-quality GaN and p-type GaN. Next, we discuss early GaN LEDs and the development of InGaN heterojunction- and quantum-well LEDs. We then summarize later developments on improved light extraction efficiency (LEE) and internal quantum efficiency (IQE), followed by a discussion of white LEDs. Finally, we highlight future directions in visible-light communication (VLC), laser-based lighting, and micro-pixel displays. For further details, we point the reader to several additional accounts of the history of blue LEDs [5–8] and the official Nobel Lecture publications [9–11]. Fig. 1 shows a generic schematic of an LED.

2. Material breakthroughs for high-quality GaN

Several critical materials breakthroughs were needed to set the foundation for the first blue GaN-based LEDs. The development of low temperature buffer layers was particularly important for achieving high quality GaN films since effective buffer layers between the substrate and active layers reduce the dislocation density in materials grown on lattice mismatched substrates. In 1983, Yoshida et al. grew GaN films by reactive molecular beam epitaxy (MBE) using an AlN buffer layer [12]. In 1986, Amano et al. grew GaN films with smooth surface morphology and low residual carrier concentration ($\sim 10^{17}$ cm^{-3}) by MOCVD using an AlN buffer, which was an important milestone [13]. Nakamura et al. later developed a two-flow MOCVD reactor with low carrier gas flow to grow very uniform and high-quality GaN on two-inch substrates [14]. The main breakthrough in this novel design was the use of a subflow, which improved the thermal boundary layer

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