Enhancing Solid-State Lighting Efficiency in GaN/InGaN Materials:

Injection Efficiency, P-type doping and structural optimization

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CONTENTS

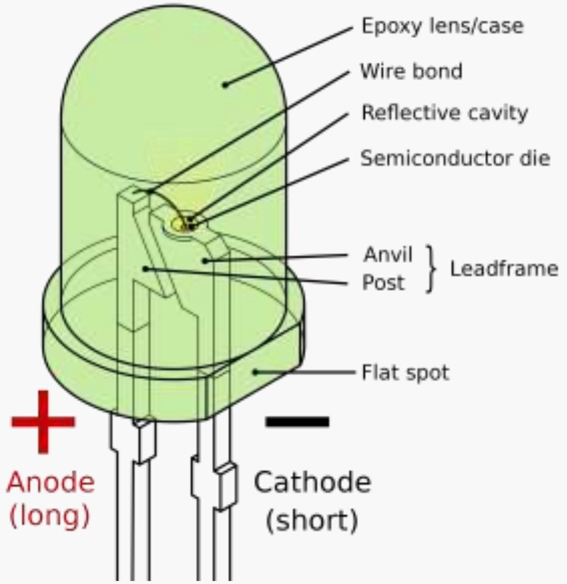
PART 01

Introduction

Why do we choose GaN/InGaN LED

Introduction

evolution of lighting technology



Incandescent Light bulb

Most electrical energy transformed into heat

Efficiency improvement limited by operating temperatures

Fluorescent Lamp

Contains harmful substances such as mercury

Harmful to both the environment and humans

Light Emitting Diode

Effective, Energy-efficient, Environmental-friendly

Emit light of different colors by adjusting the bandgap width

[1] "Light-emitting diode." Wikipedia. https://en.wikipedia.org/wiki/Light-emitting_diode.

Introduction

The early developmental background of LEDs and the limitations of the AlGaAs/GaAs material system

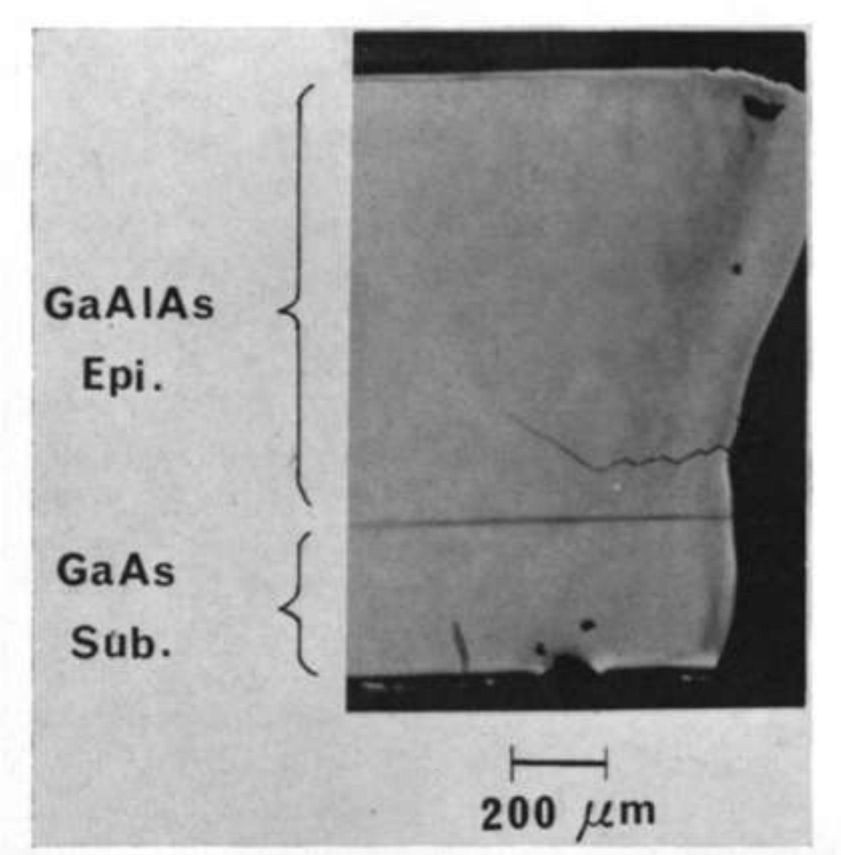


Figure 2 | An optical photograph of a section of the GaAlAs wafer

[2] S. Kishino, M. Ogirima, T. Kajimura, and K. Kurata, "Lattice Mismatch at the Interface in GaP-GaP and GaAlAs-GaAs Epitaxial Growth," in Journal of Crystal Growth, vol. 24/25, pp. 266-271, 1974.

1: Early Discoveries (Since 1907)

•1907: H. J. Round observed electroluminescence in SiC for the first time.

•1950s: Heinrich Welker introduced III-V compound semiconductors and began research on GaAs.

2: Development of Red LEDs (1960s)

•1962: N. Holonyak used GaAsP to create the world's first visible red LED.

3: The GaAsP and AlGaAs Material Systems (1970s-1980s)

4: Limitations of the Material Systems

•The GaAsP and AlGaAs material systems faced issues such as low luminous efficiency and lattice mismatch.

•When the Al content in the AlGaInP and AlGaAs/GaAs material systems exceeds 53%, they transition from a direct band gap to an indirect band gap, which reduces the radiative recombination efficiency and thereby **limiting the preparation of short-wavelength** high-brightness LEDs

Introduction

GaInN/GaN Material System - The Mainstream in LED Research

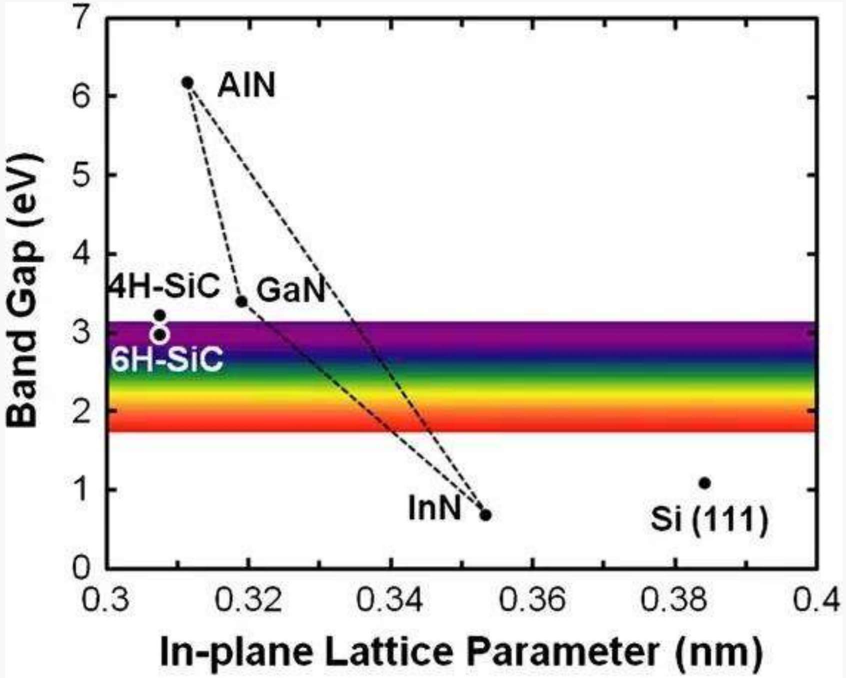


Figure 3 | The variation of the bandgap width in III-V semiconductors with the change in lattice constants at room temperature

1990s: GaInN material system gained attention for its potential in developing short-wavelength visible light LEDs.

Adjustable bandgap width:

GaInN's bandgap width can be continuously adjusted from InN's 0.7eV to GaN's 3.4eV by varying the **In** component.

(Ability to cover a wide spectrum from ultraviolet to blue-green light)

Introduction

GaInN/GaN Material System - Technological Breakthroughs

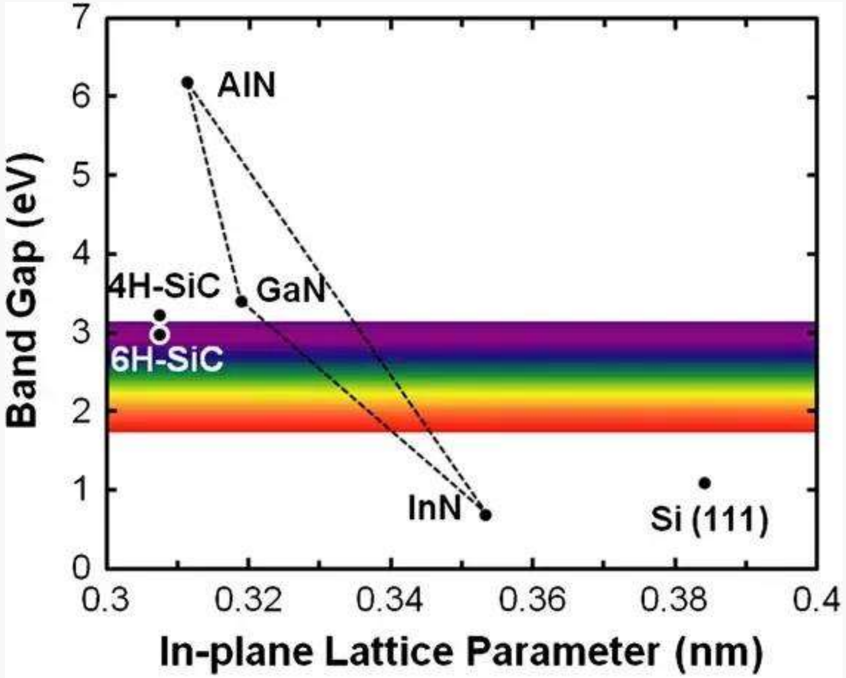


Figure 3 | The variation of the bandgap width in III-V semiconductors with the change in lattice constants at room temperature

Key Breakthroughs in GaInN Technology

Buffer layer technology: By introducing a low temperature AlN buffer layer between GaN and the substrate material, we can effectively reduce lattice mismatch, thereby improving the quality of the GaN thin film.

P-type doping technology: The breakthrough in p-type doping allows us to effectively introduce holes into GaN materials, which is crucial for the manufacture of high-efficiency LEDs.

PART 02

Challenges of Gallium Nitride-based LEDs

Difficulty of p-type doping: injection efficiency

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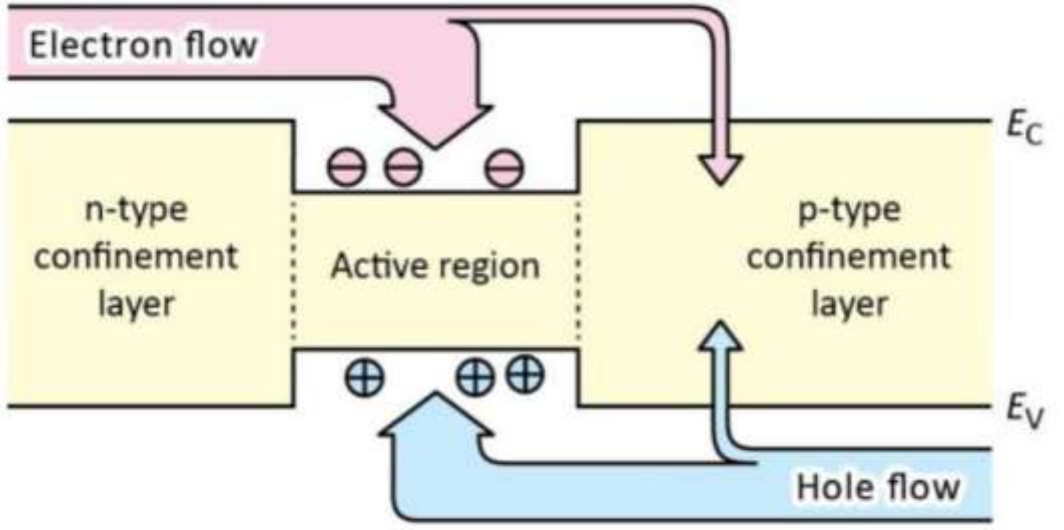


Figure 4 | Injection efficiency(IE) of carriers into active region

$$IE = \frac{\text{number of electrons injected into active region per second}}{\text{number of electrons injected into LED per second}}$$

Influence of injection efficiency on lighting

- Not all carriers are injected into the active region of an LED. Some carriers may **leak out** of the active region or traverse the active region without being captured.
- The Carrier Injection Efficiency (IE) is defined as the probability that electrons are injected into the active region. Lower IE can imply more electron leakage and less efficient light emission

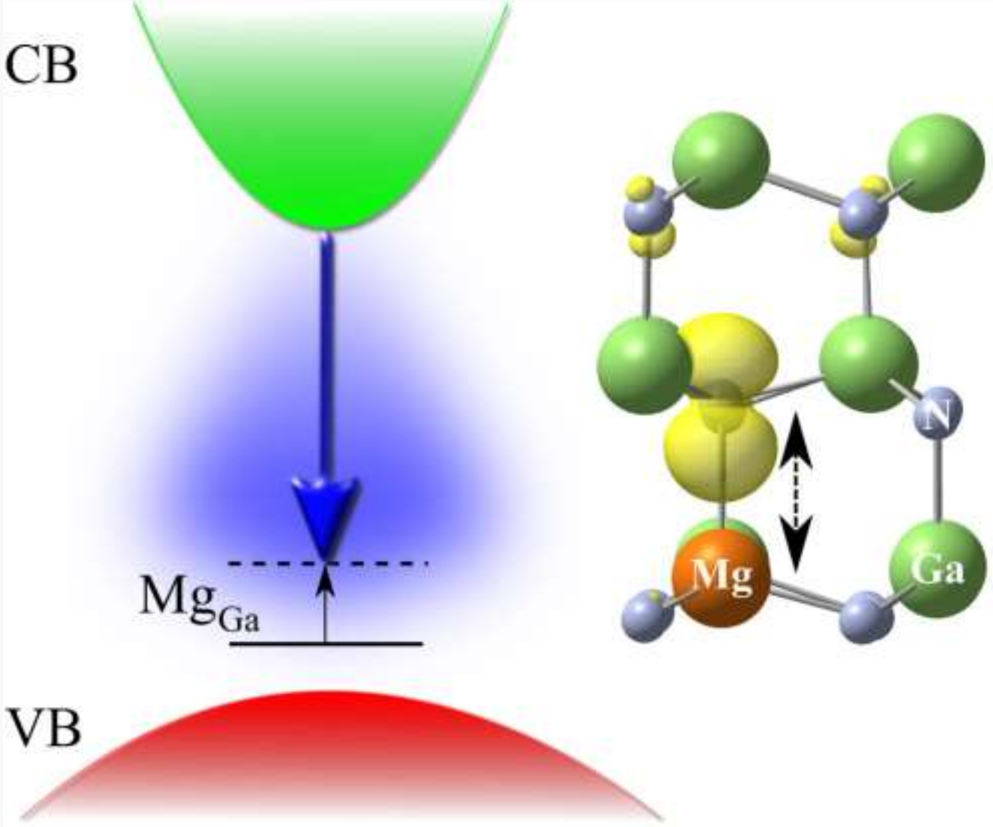


Figure 5 | Mg for P-Type Doping in GaN

Why Choose Mg for P-Type Doping in GaN

- **Valence Electrons**: Mg has two valence electrons, creating "holes" for current flow in GaN lattice.
- **Energy Level**: Mg's acceptor energy level in GaN facilitates p-type doping.
- **Chemical Stability**: Mg remains stable during high-temperature processes.
- **Ionic Radius**: Ionic radius of Mg is similar to that of Ga, so Mg integrates well into the GaN lattice.
- **Challenge**: High ionization energy of Mg requires high-temperature annealing.

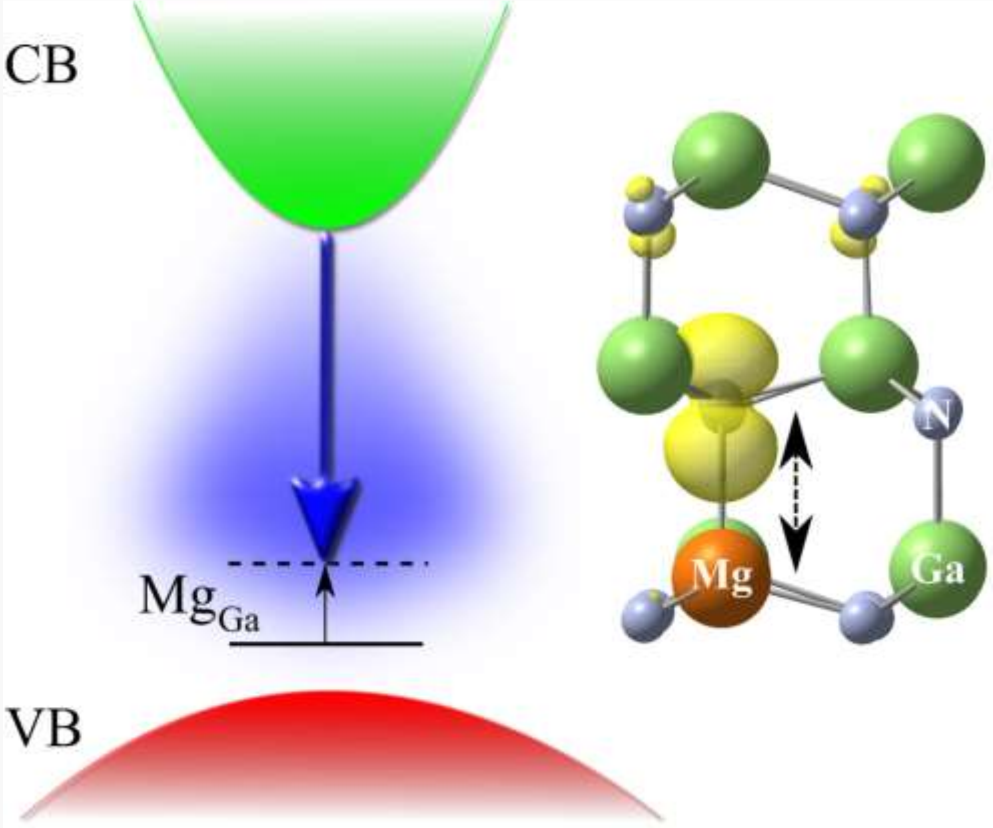


Figure 5 | Mg for P-Type Doping in GaN

Challenges in P-Type Doping in GaN

- **Effective Mass of Holes:** Holes have larger effective mass than electrons, leading to different diffusion lengths and lower mobility.
- **Carrier Concentration**: Undoped GaN has high background carrier (electron) concentration at room temperature, up to 10^17 cm^-3, making p-type GaN difficult to achieve. The hole concentration obtained from p-type doping is still significantly less than the electron concentration from n-type doping**.**
- **So we need to make the concentrations of holes and electrons in the quantum well more matched**
- **Electron Blocking Layer and V-Pits:** These factors **affect hole injection**, complicating p-type doping and reducing its efficiency**.**

PART 03

Innovative Solutions

Electron Blocking Layer& V pit

Influence of Electron Blocking Layer on Hole Injection

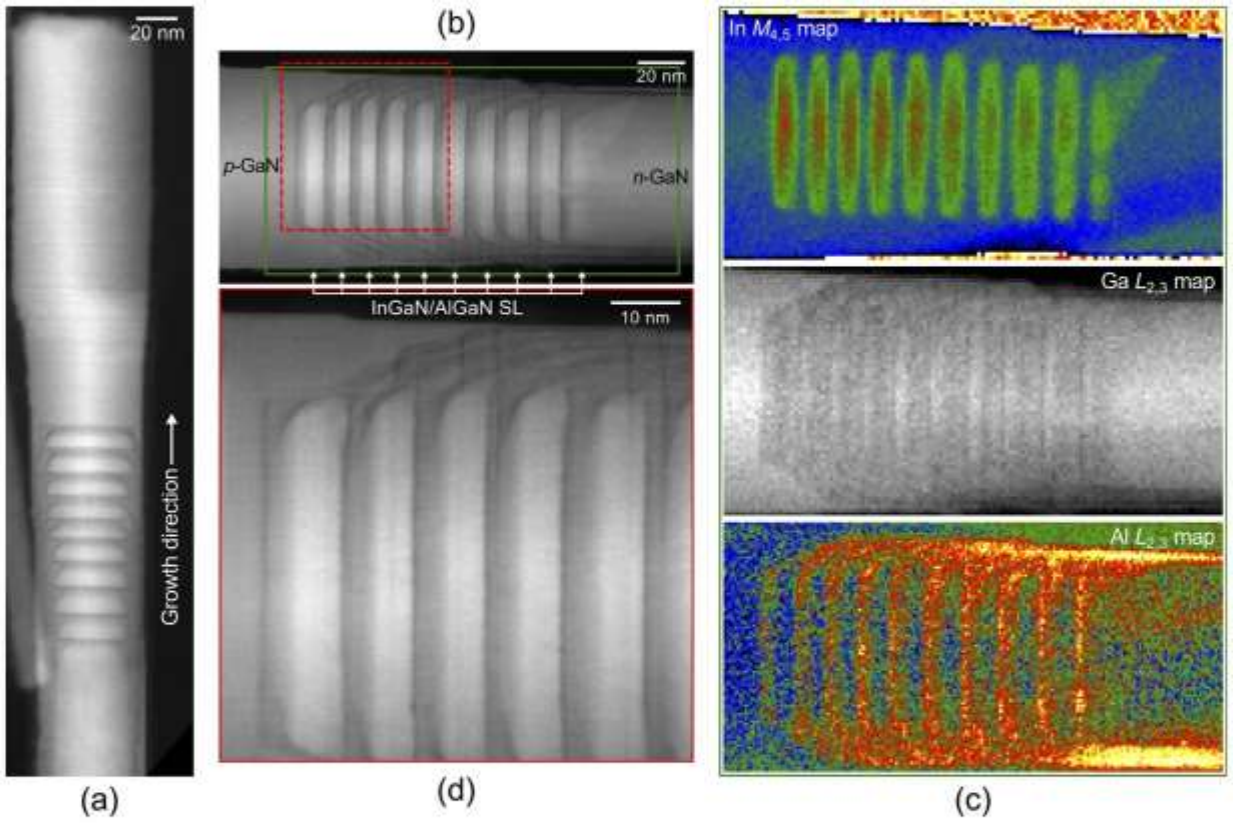
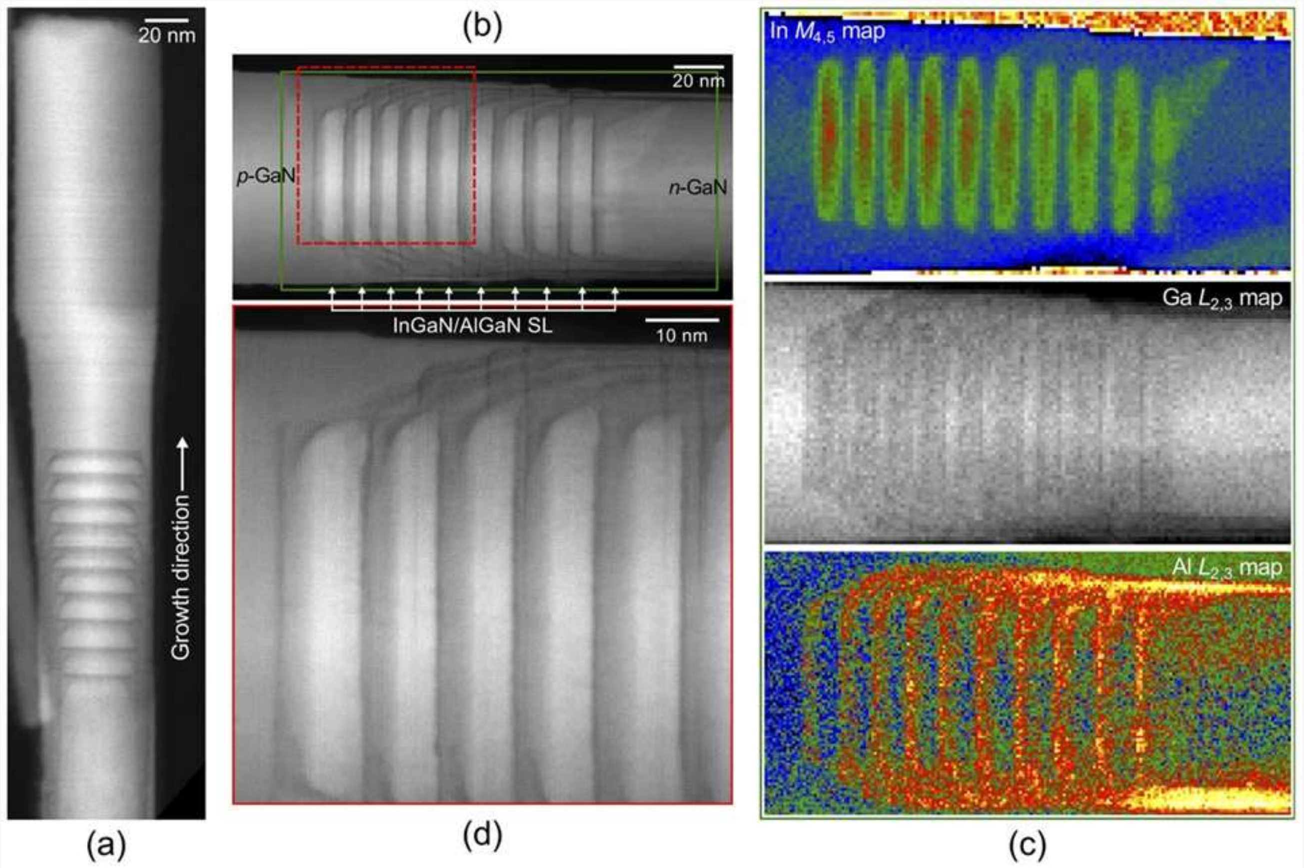


Figure 6 | InGaN/AlGaN Superlattices in Nanowire LEDs

- The electron blocking layer, typically composed of p-AlGaN**, prevents electron leakage from quantum wells to the p-layer.**
- But, the strong polarization field between the GaN barrier and the p-AlGaN electron blocking layer results in band bending, **creating a barrier to hole injection into the quantum well**.
- **Strategies** to enhance hole injection include increasing hole concentration in the electron blocking layer, for example, by doping high concentrations of Mg into the p-AlGaN electron blocking layer.
- Or, Innovative InGaN/AlGaN Superlattices in Nanowire LEDs

[3] Nguyen, H., Djavid, M., Woo, S. et al. Engineering the Carrier Dynamics of InGaN Nanowire White Light-Emitting Diodes by Distributed p-AlGaN Electron Blocking Layers. Sci Rep 5, 7744 (2015). https://doi.org/10.1038/srep07744



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Innovative InGaN/AlGaN Superlattices in LED

- The new InGaN/AlGaN superlattice structure, where InGaN and AlGaN are alternately stacked in a specific periodic pattern. The distributed AlGaN EBL layers act as multiple barriers, enabling tunnel injection of electrons and significantly reducing the hot carrier effect.
- The p-doped AlGaN barrier layers can function as distributed electron blocking layers (EBLs), which is found to be more effective in reducing electron overflow, compared to the conventional AlGaN EBL.

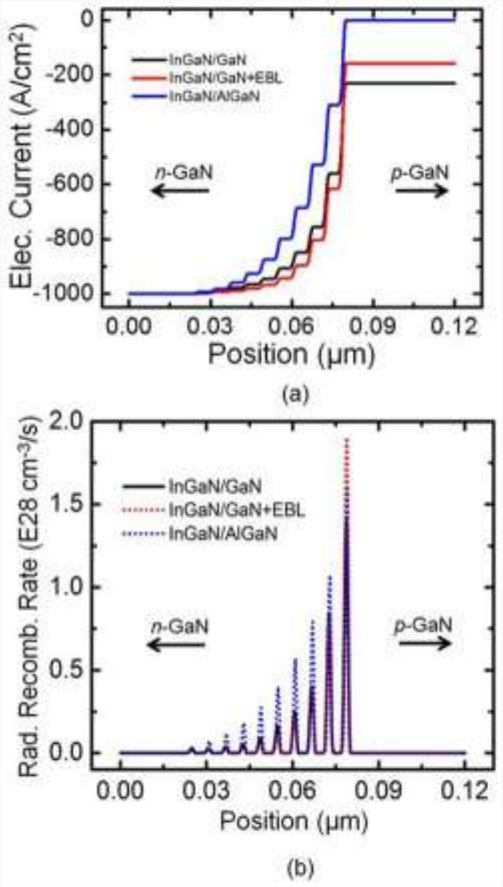

Figure 7 | (a) Simulated electron current density for the InGaN/AlGaN LED (blue), the InGaN/GaN LED with an equivalent electron blocking layer (EBL) (red), and the InGaN/GaN LED (black). (b) Simulated radiative recombination coefficients of the InGaN/AlGaN LED (dotted blue), the InGaN/GaN LED with an EBL (dotted red), and the InGaN/GaN LED (solid black) at an injection current of 1000 A/cm2
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Impact of V-Pits on Hole Injection

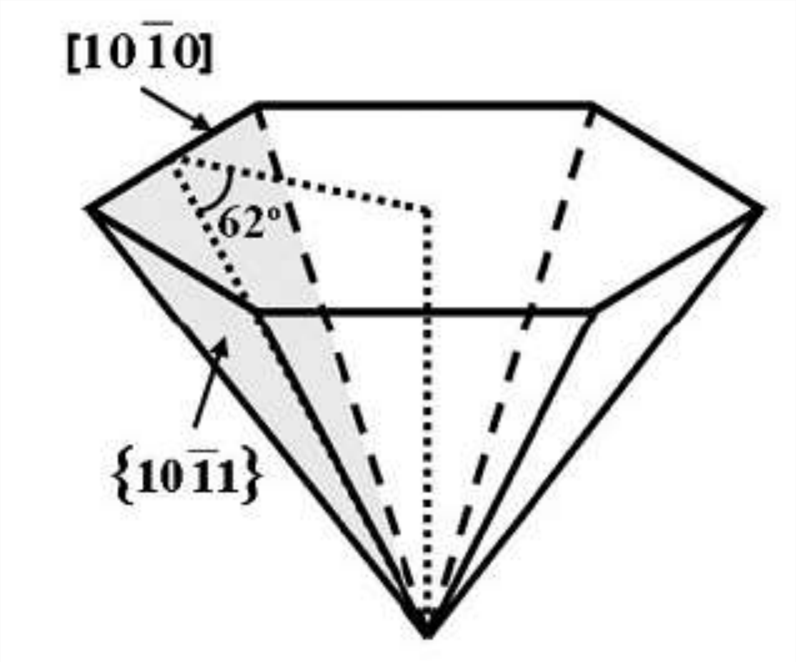


Figure 8 | Schematic diagram of the V-pits structure

- V-Pit Formation Mechanisms:

  Accumulated stress relaxation and low atomic surface migration rates under low-temperature growth conditions are the key mechanisms for V-pit formation.

- As shown in the figure, the V-shaped pits present an inverted hexagonal cone shape. The hexagonal upper surface is the (0001) plane, the 6 triangular side faces are the (10-11) planes, and the angle between the side face and the upper surface is about 62°, while the angle between the two opposite side faces is about 56°

Impact of V-Pits on Hole Injection

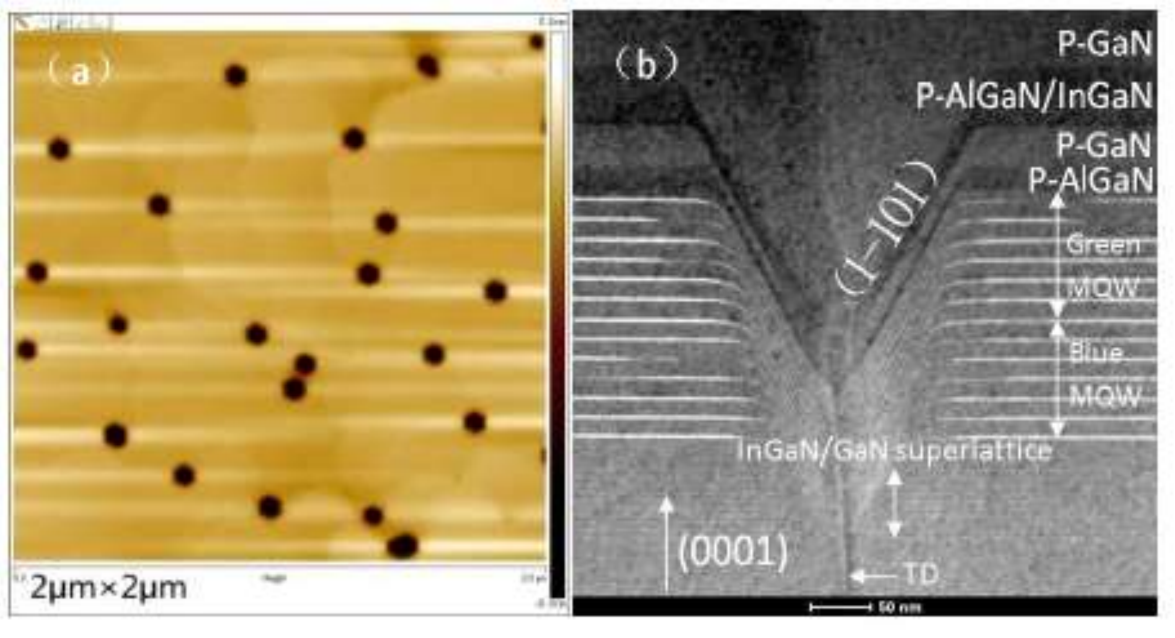
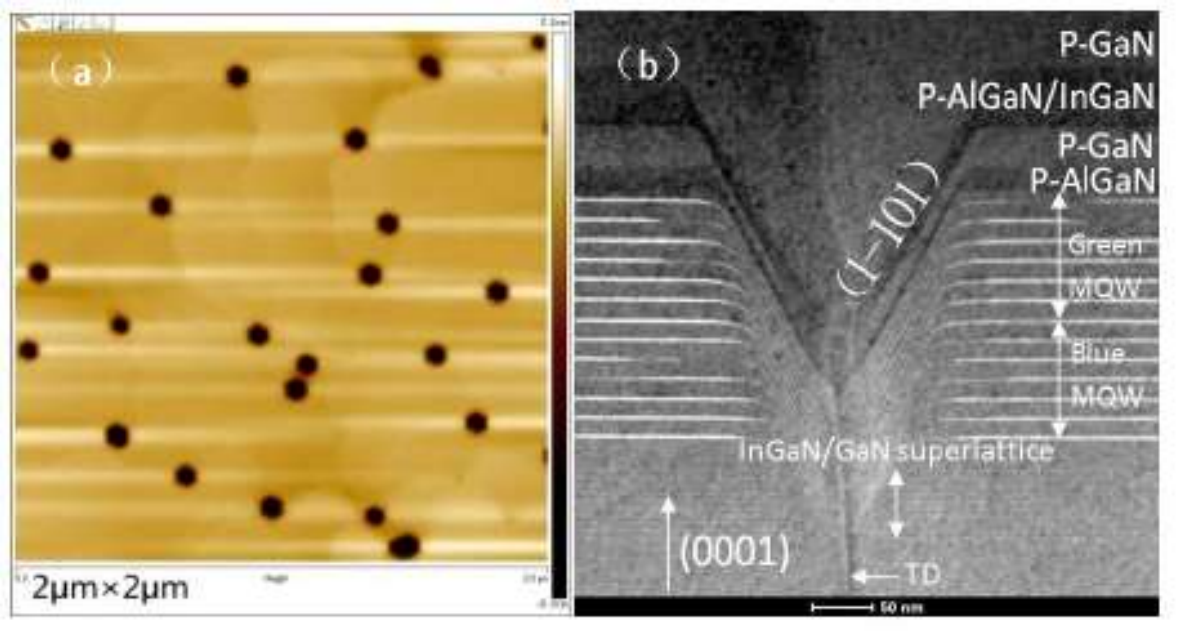


Figure 9 | (a)AFM morphology of the InGaN/GaN superlattice surface, image size: 2μm×2μm; (b) is the STEM morphology of the InGaN/GaN green light multi-quantum well structure

- V-Pits are inherent defects in GaN materials that have significant effects on hole injection and transmission.
- **Hole Injection Pathways:** Holes can be injected directly into the quantum well from the (0001) plane, or they can be injected through the sidewalls of V-pits, the latter of which improves hole injection efficiency.
- V-Pits also contribute to improved distribution uniformity of holes within the well, reducing efficiency droop under high current and improving light output efficiency.

[5] X. Liu, J. Liu, Q. Mao, et al “Effects of p-AlGaN EBL thickness on the performance of InGaN green LEDs with large V-pits,” [J]. Semiconductor Science and Technology, vol. 31, p. 025012, 2016.

Impact on Quantum Efficiency



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- Impact of V-Pits on Hole Injection and Quantum Efficiency

  1. V-pits in multi-quantum well structures serve dual functions: dislocation shielding and facilitation of hole injection into quantum wells, which enhances quantum efficiency.

  2. Due to fewer polarized charges on the V-pit sidewalls, resulting from the reduced In content in the sidewall quantum wells and the semi-polar (10-11) plane, holes more readily inject from V-pits compared to the flat regions.

[5] X. Liu, J. Liu, Q. Mao, et al "Effects of p-AlGaN EBL thickness on the performance of InGaN green LEDs with large V-pits," [J]. Semiconductor Science and Technology, vol. 31, p. 025012, 2016.

Impact on Quantum Efficiency

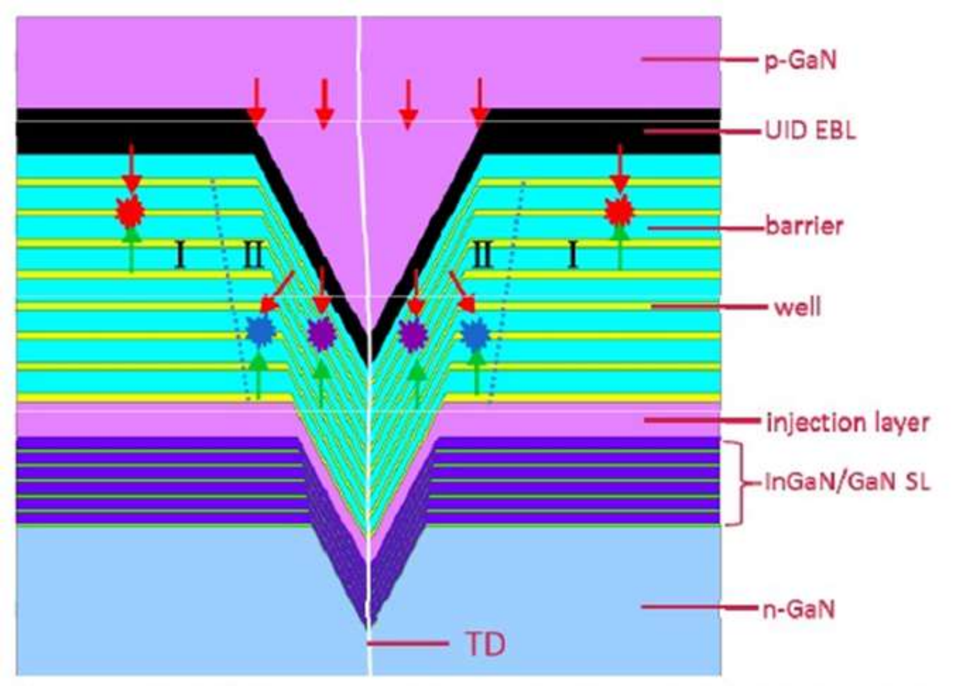

Figure 10 | The different injection paths of holes are given

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Conclusion

- Evolution of LED Technology: Material Choices and Limitations
- Application of GaN and GaInN Material Systems
- Importance of p-type Doping: The significance of p-type doping in enhancing LED performance is highlighted, especially using magnesium as the p-type dopant.
- Challenges associated with p-type doping: Hole injection efficiency, carrier concentration, and the impact of the electron blocking layer.
- Structural optimization to Enhance Lighting Efficiency: Various strategies for improving LED performance are explored, including optimizing the electron blocking layer, using InGaN/AlGaN superlattice structures, and the application of V-pits. These strategies aim to enhance the uniform distribution of carriers and light emission efficiency.