

Article

Enhanced P-Type GaN Conductivity by Mg Delta Doped AlGa_N/Ga_N Superlattice Structure

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Abstract: A method of combining the AlGa_N/Ga_N superlattices and Mg delta doping was proposed to achieve a high conductivity p-type GaN layer. The experimental results provided the evidence that the novel doping technique achieves superior p-conductivity. The Hall-effect measurement indicated that the hole concentration was increased by 2.06 times while the sheet resistivity was reduced by 48%. The fabricated green-yellow light-emitting diodes using the achieved high conductivity p-type GaN layer showed an 8- and 10-times enhancement of light output power and external quantum efficiency, respectively. The subsequent numerical calculation was conducted by using an Advanced Physical Model of Semiconductor Device to reveal the mechanism of enhanced device performance. This new doping technique offers an attractive solution to the p-type doping problems in wide-bandgap GaN or AlGa_N materials.

Keywords: GaN; p-conductivity; superlattice; delta doping; LED



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1. Introduction

III-Nitride and related alloys are attractive materials due to their immense potential in optoelectronic applications including the ultraviolet and visible range [1–9]. The well-known Mg is generally used as p-type dopant for GaN based devices. However, Mg has a large acceptor ionization energy E_A (~200 meV) at room temperature which is much larger than the donor (Si generally) activation energy E_D (~15 meV) in GaN [10]. Therefore, lower acceptor ionization rate becomes an obstacle to obtain high conductivity p-type GaN. P-type GaN was earlier realized by electron irradiation beam and thermal annealing, respectively [11,12], but so far, a high conductivity p-GaN ($>10^{18}$ cm⁻³) epilayer is still difficult to achieve. Heavy Mg doping seems like the most effective way to achieve a high hole concentration of p-type GaN epilayer, but the hole mobility will decrease due to the serious impurity scattering. Furthermore, the increased dopant concentration will lead to a degradation of GaN epilayer crystalline quality. Various methods have been proposed to improve p-conductivity in GaN. Kozodoy et al. utilized the AlGa_N/Ga_N superlattice (SLs) structure only doping in the interface to promote the Mg acceptor ionization [13]. However, this discontinuous doping method will lead to the existence of discontinuous high resistivity areas. Simon et al. proposed a polarization-induced hole doping method with a compositionally graded Al_xGa_{1-x}N layer [10]. However, the polarization electric field is not strong enough to ionize a large number of Mg dopants. In recent years, there have been many other attempts to increase hole concentration in GaN [14–17]. In this work, a method of combining the AlGa_N/Ga_N SLs and Mg delta doping is proposed to achieve

high conductivity p-type GaN, which is realized by acceptor doping in the whole p-type region but increasing the doping concentration at the AlGa_{0.95}N/GaN interface to improve the p-type conductivity. This method not only resolves the problem of existence of high resistance areas of discontinuous doping method, but also utilizes the polarized electric field adequately. Furthermore, a systematical study about the influence of the new p-type technique on the performance of green-yellow light emitting diodes (LED) is performed both numerically and experimentally.

2. Materials and Methods

In order to investigate the influence of novel doping method on the p-conductivity of GaN film, two p-GaN structures were grown by AIXTRON CRUIS I metal-organic chemical vapor deposition (MOCVD) system on the c-plane patterned sapphire substrates (PSS). Figure 1a–b show the two p-GaN sample structures which are named sample A and sample B, respectively. The structures of two p-GaN are identical before Mg doping p-type layer, which contain unintentionally doped GaN layer, Al_{0.05}Ga_{0.95}N electron blocking layer (EBL), and Mg doped p-type layer. The p-type layer for sample A was uniform Mg doped GaN layer which was used as reference sample. Triethylgallium, trimethylaluminium, and ammonia were used as source compounds. Hydrogen gas was the carrier gas. Bis-cyclopentadienyl-magnesium (CP₂Mg) was used as a Mg dopant source and the CP₂Mg flow was kept at 1500 sccm. For sample B, the p-type layer was divided into three parts. The top and bottom parts were uniform Mg doping GaN layer. A 9-periods p-type 4-nm-Al_{0.05}Ga_{0.95}N/3-nm-GaN structure was adopted in the middle part of sample B. In order to achieve delta doping at the SLs structure in sample B, the flow of CP₂Mg was constant throughout the entire p-type layer growth, while the growth process had a 6-s pause at each SL interface and the Mg source was still opened. This growth process leads to an intentional increased concentration of Mg dopants at the SLs interfaces and actually implements a Mg delta doping in the middle part of sample B. To further verify the improvement of device performance by novel doping technique, two green-yellow light emitting diodes (LED) are fabricated using the two different p-type GaN layer. Figure 2 shows the structure diagram of the InGa_{0.45}N/GaN multi-quantum wells (MQWs) based LED structure used in this work. An undoped GaN layer is followed by a Si doped GaN layer. The 60-nm-thick In_{0.05}Ga_{0.95}N/GaN SLs are employed to regulate the stress. The InGa_{0.45}N/GaN MQWs consist of ten 2 nm In_{0.45}Ga_{0.64}N quantum wells embeds in eleven 15 nm GaN quantum barriers. The In_{0.45}Ga_{0.64}N/GaN MQWs are terminated by an Al_{0.05}Ga_{0.95}N EBL. The top of the LED structure is the Mg doped p-type layer. The LED A adopts the uniform Mg doped p-GaN layer while LED B adopts the p-type layer structure of sample B above. After the growth, standard chip processing is carried out and the size of the LED chip is 300 µm × 325 µm. In order to reveal the mechanism of enhanced p-conductivity and device performance, an Advanced Physical Model of Semiconductor Device (APSYS) simulation is adopted based on the structure above. The main parameters set in the simulation are the polarization shielding coefficient of 0.5, the auger composite coefficient of $1 \times 10^{-43}/(\text{m}^6 \cdot \text{s})$, the band offset ratio of 0.7 and the carrier lifetime of 10 ns.

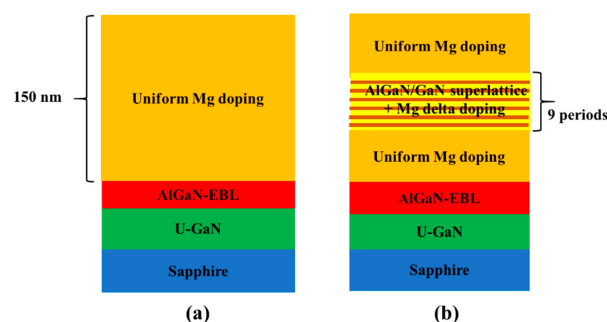


Figure 1. Structure diagrams of p-GaN: (a) sample A and (b) sample B.

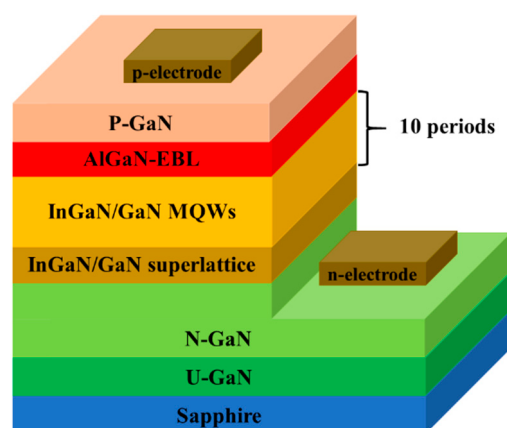


Figure 2. Structure diagram of green-yellow LED.

3. Results and Discussions

Figure 3 shows the cross-sectional transmission electron microscope (TEM) image of sample B, the p-GaN layer and the structure of AlGaIn/GaN SLs can be clearly observed. The TEM image was acquired using a Tecnai G2 F20 S-Twin (FEI, Hillsboro, OR, USA) operating at 200 kV.

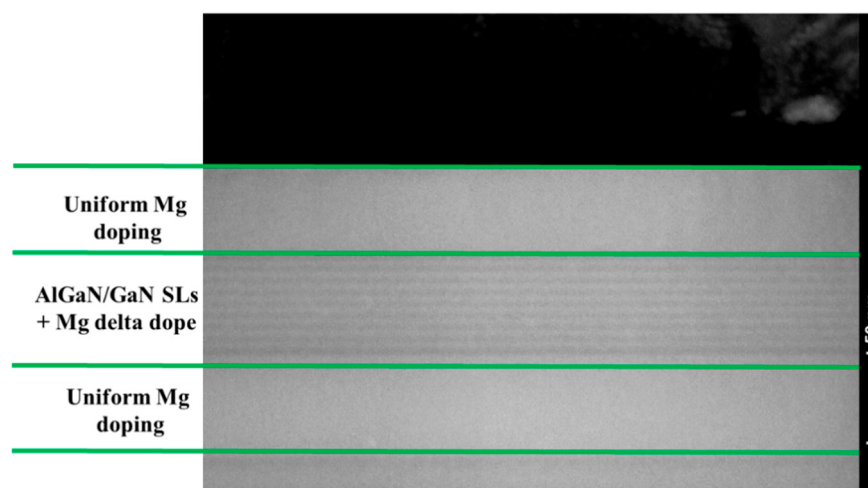


Figure 3. Cross-sectional TEM image of the p-type layer of sample B.

To characterize the different conductivities of the two p-GaN samples, the Hall-effect measurement was performed at room temperature using a Lake Shore 8400 Series at a magnetic field of 0.5 T. The measured hole concentrations, hole mobilities, and sheet resistivities are shown in Table 1. From the Hall-effect measurements, the hole concentration of sample B is $3.1 \times 10^{18} \text{ cm}^{-3}$, which is 2.06 times higher than that of sample A, and it is an order of magnitude higher than previous reported hole concentration of p-GaN grown by MOCVD [18–20]. At the same time, as shown in Table 1, the increased impurities and interface scattering at interface of AlGaIn/GaN SLs in sample B also lead to a decrease of hole mobility, but the sheet resistivity still decreases significantly due to the large hole concentration.

Table 1. Results of the Hall measurement of the samples at room temperature.

p-GaN	Hole Concentration ($\times 10^{18} \text{ cm}^{-3}$)	Mobility ($\text{cm}^2/\text{V}\cdot\text{s}$)	Sheet Resistivity ($\Omega/\square$)
Sample A	1.5	10.0	34,407
Sample B	3.1	7.5	17,951

In order to verify the effectiveness of p-conductivity on the performance of LED, Figure 4a shows electroluminescence (EL) spectra of LED A and LED B at the injection current of 20 mA. As illustrated in Figure 4a, the peak emission wavelengths of both samples are around 559 nm and the EL intensity of LED B is significantly enhanced compared with that of LED A. Figure 4b,d show the voltage, light output power (LOP) and external quantum efficiency (EQE) as functions of the injection current. It can be clearly observed that the voltage of LED B is significantly lower than that of LED A at the same injection current. The LOP and EQE of LED B have about an order of magnitude improvement than that of the LED A. At an injection current of 20 mA, the peak wavelengths are 559.3 and 559.6 nm for LED A and LED B, respectively. The LOP of LED A is 1.03 mW and the EQE is 1.32% while LED B has a higher LOP and EQE which are 8.7 mW and 13.4%. Obviously, the improved p-conductivity significantly enhanced the performance of GaN based LED. In previous work, the optimization of the growth conditions and MQWs structures were proposed to achieve high performance GaN based LED. Lai et al. demonstrated a high-efficiency yellow-green LED with the peak wavelength of 560.7 nm at 20 mA. The reported EQE was 2.1%, which is significantly lower than LED B [21]. Saito et al. reported a LED on *c*-face sapphire substrate with wavelength of 559 nm, the LOP was 11 mW at an injection current of 20 mA [22]. However, the voltage of the report LED was 5.71 V when the injection current is 20 mA, which is much higher than the LED B in this work (3.9 V). Du et al. fabricated a LED chip on *c*-plane sapphire substrate with a size of $300 \times 300 \mu\text{m}^2$. But the dominant wavelength and output power at 20 mA were 556.3 nm and 0.24 mW, respectively [23]. Compared with the previous reports, the performance of LED B has obvious advantages, which demonstrates that the novel technique of p-type doping in this work is very promising for the achievement of high-efficiency GaN based LED.

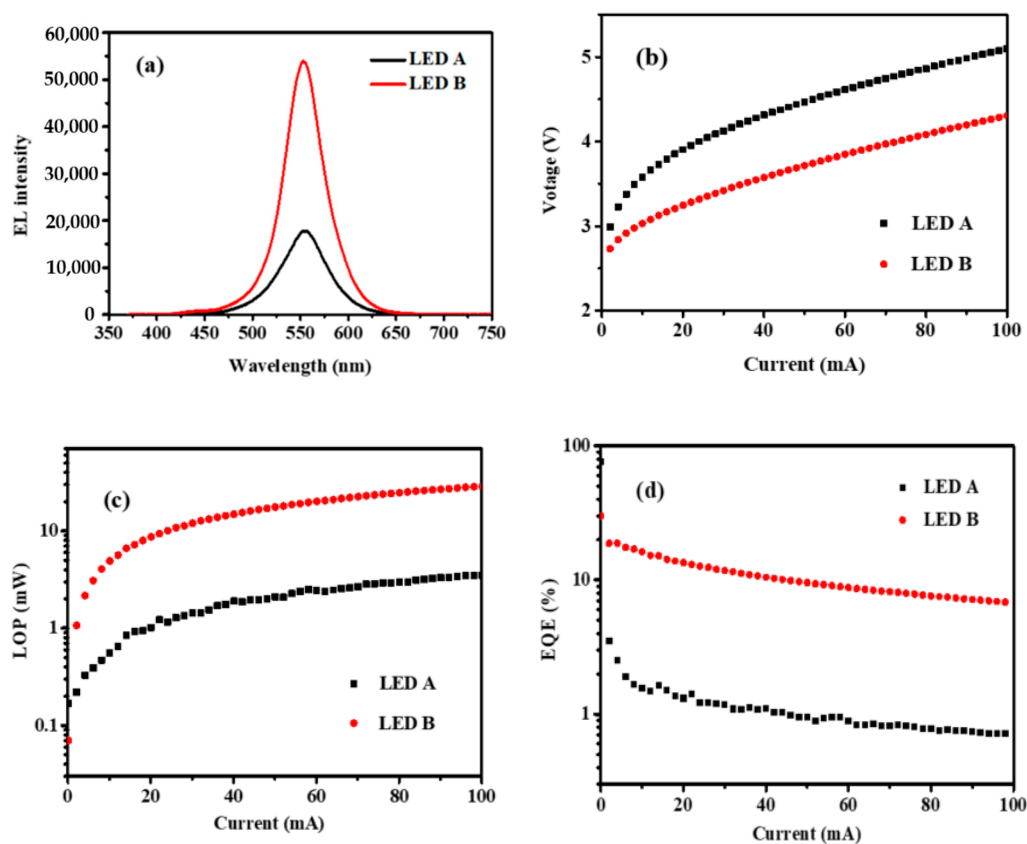


Figure 4. (a) Electroluminescence (EL) spectra, (b) Voltage, (c) light output power (LOP), and (d) external quantum efficiency (EQE) as a function of the injection direct current of the green-yellow LED, respectively.

In order to clarify the mechanism of novel doping methods enhanced the p-conductivity of GaN film, the calculated hole concentrations distributions and energy band diagrams of sample B are given in Figure 5, which are performed by the commercial simulation software APSYS. Figure 5a shows the simulated hole concentration of both sample A and sample B, which indicated that the hole concentration is significantly increased in the middle layer of sample B by the novel p-doping structure. To illustrate the mechanism of hole concentration enhancement, the simulated energy band of sample B is shown in Figure 5b, and the up and down blue lines correspond to the conduction and valence band edges, respectively. The periodic AlGaIn/GaN SLs structure generated a periodic oscillation of the energy-band edge can be observed. The sharp discontinuity of the polarization field at abrupt AlGaIn/GaN heterojunction interface leads to the formation of a bound sheet charge at the heterointerface and generated a strong electric field. Because the Mg acceptors are favorable to ionize at the band edge trending down, the intentionally increased Mg dopants at SL interface will effectively utilize the polarization field to increase the ionization rate of Mg dopant and enhance the hole concentration [24].

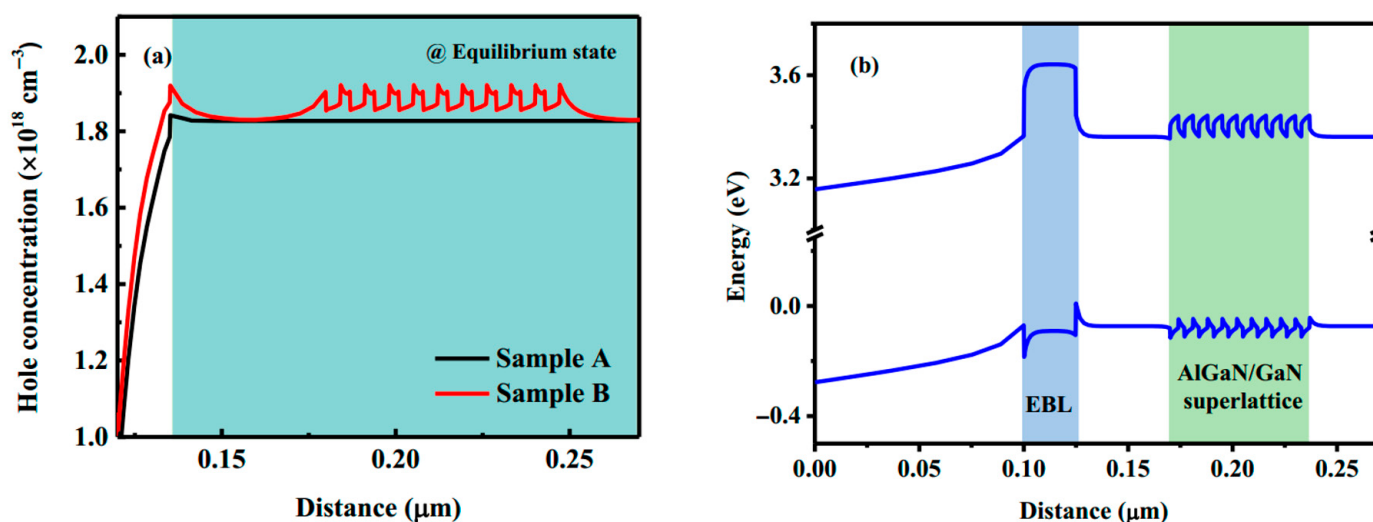


Figure 5. (a) Simulated hole concentration of both sample A and sample B, and (b) Simulated energy-band diagram of sample B.

In addition, for take a deep insight into the improved p-conductivity on the performance of LED, the APSYS simulated results of LED performance is presented in Figure 6. Figure 6a–c show the simulated I–V curves, light output power (LOP), and wall plug efficiency (WPE) varied with injection current. It is clearly that the LED B exhibit lower voltage, higher LOP and WPE under the same injection current compared with LED A. The simulated results implied that the LED performance is enhanced due to the adoption of the novel p-doping structure, which is consistent with the experimental results.

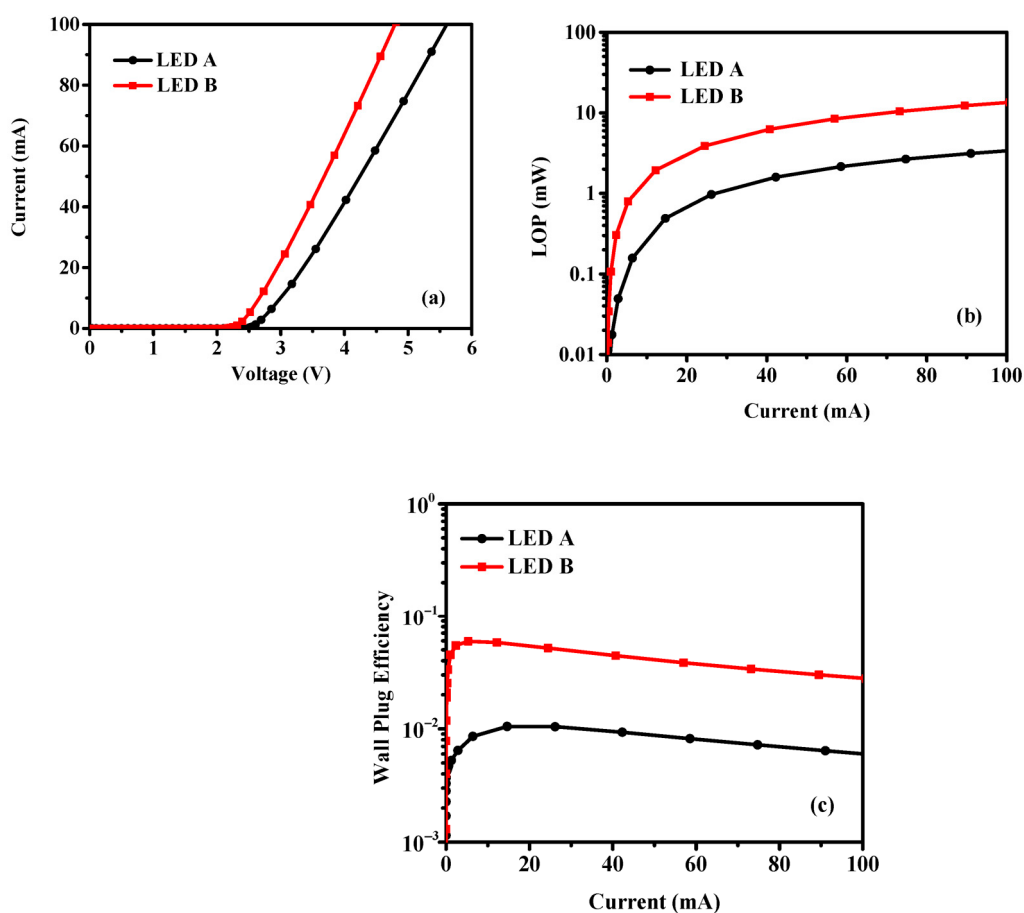


Figure 6. Advanced Physical Model of Semiconductor Device (APSYS) simulated results of LED A and LED B: (a) Voltage, (b) LOP and (c) WPE as a function of the injection direct current.

4. Conclusions

In summary, we proposed a method of combining the AlGaIn/GaN SLs and Mg delta doping to achieve a high conductivity p-type GaN. Hall-effect measurement showed the hole concentration of sample B was increased by 2.06 times while the sheet resistivity was reduced by 48% compared to sample A. In order to verify the enhancement of the GaN based photoelectric device performance by improved p-conductivity, a green-yellow LED was fabricated using the optimized high conductivity p-GaN layer and the EQE was increased by 10 times. The APSYS simulated results illustrated the enhancement mechanism of p-conductivity and LED performance. The novel technique of p-type doping in this work are very promising for the achievement of high-efficiency GaN based LEDs and electronic devices.

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