Effects of p-type GaN thickness on optical properties of GaN-based light-emitting diodes*

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The influence of p-type GaN (pGaN) thickness on the light output power (*LOP*) and internal quantum efficiency (*IQE*) of light emitting diode (LED) was studied by experiments and simulations. The *LOP* of GaN-based LED increases as the thickness of pGaN layer decreases from 300 nm to 100 nm, and then decreases as the thickness decreases to 50 nm. The *LOP* of LED with 100-nm-thick pGaN increases by 30.9% compared with that of the conventional LED with 300-nm-thick pGaN. The variation trend of *IQE* is similar to that of *LOP* as the decrease of GaN thickness. The simulation results demonstrate that the higher light efficiency of LED with 100-nm-thick pGaN is ascribed to the improvements of the carrier concentrations and recombination rates.

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Recently, high performance InGaN/GaN light-emitting diodes (LEDs) have been widely used in full color display, liquid crystal display backlight and semiconductor lighting field[1,2]. Although the luminous efficiency of GaN based LED has been significantly increased in the last few years[3], the quantum efficiency still decreases at high injection current, so-called efficiency droop[4,5]. The poor hole injection efficiency into the InGaN/GaN active layer is considered to be the key role of the droop effect because of the heavy hole effective mass and the low hole concentration[6,7]. The growth temperature of p-type GaN (pGaN) layer greatly affects the crystal qualities of quantum wells and the optical properties of the LED[8]. A rough pGaN layer can obviously enhance the light output power (*LOP*) of GaN-based LED[9,10]. Actually, the thickness of total p-type layer has significant influence on the light extraction efficiency in flip-chip LEDs[11]. Liao et al[12] studied the effect of the thermal annealing process of the high temperature growth of pGaN layer on the InGaN/GaN quantum wells emission behaviour. Schad et al[13] investigated the transmission spectrum and absorption coefficient of pGaN layer. However, the physical mechanism of internal quantum efficiency (*IQE*) dependence of GaN-based LED on the pGaN thickness has not been reported before.

In this paper, we grew GaN-based LEDs with different pGaN thicknesses on sapphire substrate and investigated their optical properties by experiments and simulations. The LED with 100-nm-thick pGaN layer shows higher *LOP* and *IQE* compared with the others at 350 mA injection current. The theoretical arithmetic data demonstrate that the optical properties improvements of the LED sample with 100-nm-thick pGaN are ascribed to the enhancements of carrier concentrations and radiative recombination rates.

The GaN-based LEDs were grown on the 5.08-cm-thick flat sapphire substrates by metal organic chemical vapor deposition (MOCVD). At first, the substrates were cleaned in hydrogen atmosphere at 1 090 °C for 300 s. Then, the temperature of the reactor decreases to 540 °C to grow a GaN nucleation layer with a thickness of 25 nm. A 3-μm-thick undoped GaN layer and a 2.5-μm-thick Si-doped GaN layer were grown on the annealed nucleation layer at a temperature of 1 060 °C. After that, 12 pairs of InGaN/GaN mutil-quantum wells with 3-nm-thick quantum wells and 10-nm-thick quantum barriers were grown on the top of the n-type GaN. The growth temperature of the wells and barriers are 750 °C and 850 °C, respectively. At last, magnesium doped pGaN layers with different thicknesses were grown at 950 °C. The pGaN thickness was designed to be 50 nm, 100 nm, 200 nm and 300 nm for different samples. After the epitaxial growth, the wa-

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fers were defined with mesa size of 1 mm×1 mm by a standard photolithographic process and partially dry-etched down to the n-type GaN by inductively coupled plasma (ICP) technology. A transparent conduction indium-tin-oxide (ITO) thin film and Cr/Ti/Au metals were deposited as the ohmic contact layers and electrodes with an evaporation method. Fig.1 shows the diagram of GaN-based LED structure used in this study. An integrating sphere with a high-accuracy array spectrometer was used to measure the *LOP* of the LED devices with different pGaN thicknesses.

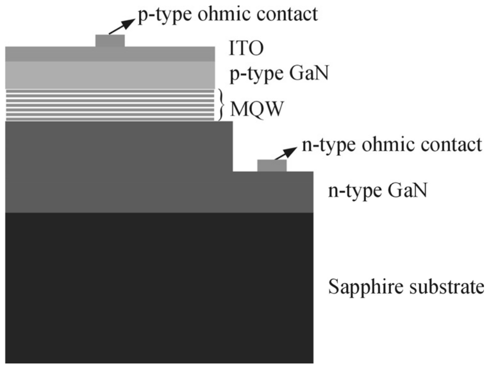
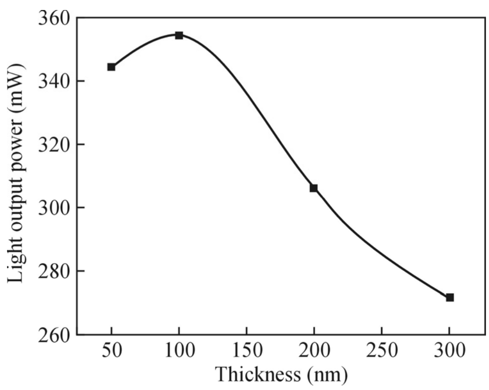


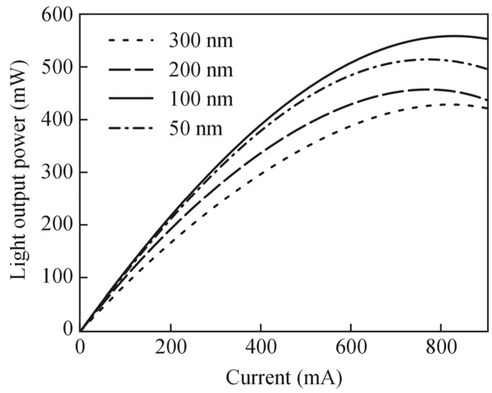
Fig.1 Cross-sectional schematic of GaN-based LED

Fig.2(a) depicts the dependence of *LOP* on the pGaN thickness at 350 mA injection current. The *LOP* of GaN-based LED increases as the pGaN thickness decreases from 300 nm to 100 nm, and then decreases as the thickness reduces to 50 nm. The *LOP* of LED with 100-nm-thick pGaN layer increases by 30.9% compared with that of LED with 300-nm-thick pGaN. In order to analyze the light output properties of LED at high injection current, we plot the *LOP* as a function of injection current for the four samples, as shown in Fig.2(b). The *LOP* of LED improves first and saturates at high current as the increase of the injection current. The GaN-based LED with 100-nm-thick pGaN keeps the highest optical power in the measured forward current regime. The experimental data show that the optimal pGaN thickness is 100 nm for the best light power.

The variable temperature photoluminescence (PL) measurements were carried out to study the *IQE* of the GaN-based LED with different pGaN thicknesses. The *IQE* is defined as the ratio of the integral PL intensity



(a)



(b)

Fig.2 (a) *LOP* as a function of the pGaN thickness; (b) *LOP*-current curves of GaN-based LED with different pGaN thicknesses

measured at 300 K to that at 10 K[14]. Fig.3 shows the dependence of *IQE* of GaN-based LED on pGaN thickness. The variation tendency of the *IQE* as a function of pGaN thickness coincides with that of the *LOP*, as shown in Fig.2(a). The results demonstrate that the *LOP* improvement of the GaN-based LED with 100-nm-thick pGaN is attributed to the enhancement of the *IQE* of the active layer.

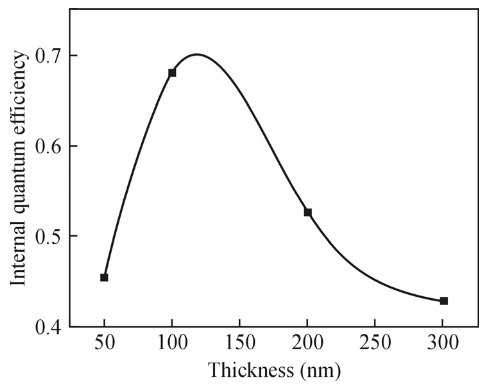


Fig.3 *IQE* as a function of the pGaN thickness

To further confirm the mechanisms of *IQE* improvement as the pGaN thickness decreases from 300 nm to 100 nm, we simulated the radiative recombination and carrier distributions of the GaN-based LED by APSYS[15]. The simulation software self-consistently solves the Poisson equation, continuity equation and Schrödinger equation with proper boundary conditions. In the simulation, the values of Shockley-Read-Hall (SRH) recombination lifetime and Auger coefficients are 50 ns and 10^{-30} cm^6/s, respectively[16,17]. The GaN-based LEDs with 100-nm-thick and 300-nm-thick pGaN layers are defined as sample A and sample B, respectively.

The calculated radiative recombination rates of the two samples are plotted in Fig.4. The radiative recombination process only happens in the quantum well areas for the both samples. The radiative recombination rate of the sample A is higher than that of the sample B. The ratio of the peak radiative recombination rate for sample A to that for sample B is defined as R_{AB}. It increases to 195% at the last quantum well from 104% at the first quantum well. The results reveal that the *IQE* enhancement of the sample A is mainly attributed to radiative recombination rate improvement of the quantum wells close to the p-GaN layer.

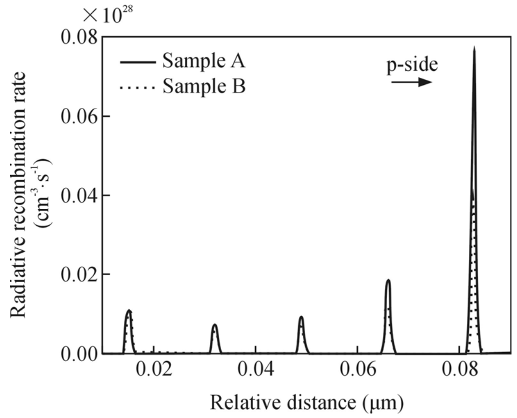
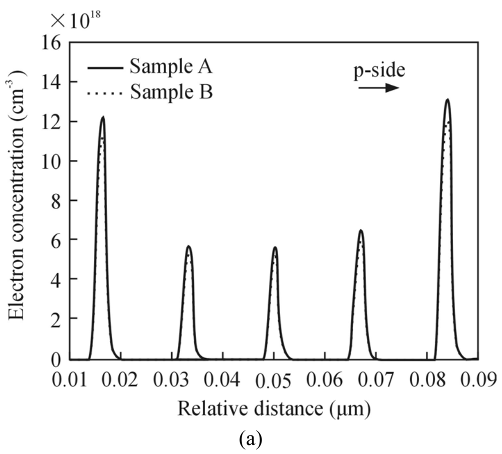


Fig.4 The radiative recombination rate distributions of the samples A and B

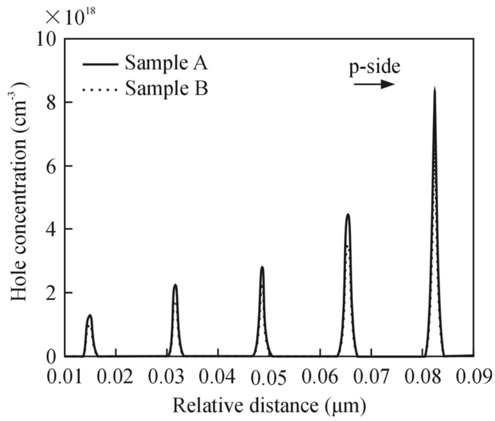
The recombination rate R can be expressed as[18]

$$R=Bnp, \quad (1)$$

where B is the recombination coefficient, and n and p are the concentrations of the electron and hole, respectively. From Eq.(1), we can easily find that the recombination rate is determined by the electron and hole concentrations. The simulated electron and hole concentrations are shown in Fig.5. It is obvious that the electrons and holes accumulate in the quantum well regions. It can be seen from Fig.5(a) that the calculated electron concentration of the sample A is higher than that of sample B in the quantum wells close to the pGaN layer. The same phenomenon can be found for the hole carrier concentration distribution, as shown in Fig.5(b). Besides, the hole concentrations decrease dramatically from the p-side layer to the n-side layer for the two samples because of its high effective mass[19]. The simulated data prove that the higher carrier concentration leads to the higher radiative recombination rate.



(a)



(b)

Fig.5 The carrier concentration distributions of the samples A and B: (a) Electron; (b) Hole

In order to quantitatively analyze the improvements of the radiative recombination rate, electron and hole concentrations for the sample A, we plot the R_{AB}, E_{AB} and H_{AB} as a function of the quantum well number, as shown in Fig.6. The ratios E_{AB} and H_{AB} are defined as the peak electron and hole concentrations of the sample A to those of the sample B, respectively. It is obvious that the R_{AB}, E_{AB} and H_{AB} improve as the increase of quantum well number. It reveals that the quantum wells close to the pGaN layer play a main role in the efficiency improvement of LED. At the last quantum well, the hole concentration of the sample A improves by 25% compared with that of sample B, while the electron concentration increases by 14%. The calculation results demonstrate that the recombination rate improvement of the GaN-based LED with 100-nm-thick pGaN is attributed to the increase of the electron and hole concentrations.

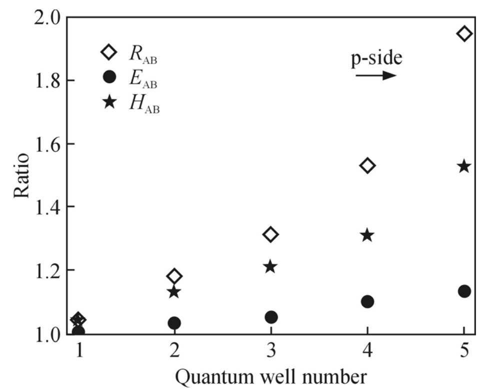


Fig.6 The ratios of R_{AB}, E_{AB} and H_{AB} in different quantum wells

In summary, we investigate the influence of the pGaN thickness on the *LOP* and *IQE* of the GaN-based LEDs by experiments and simulations. The *LOP* of the GaN-based LED improves as the pGaN thickness decreases from 300 nm to 100 nm, and then drops as the thickness reduces to 50 nm. The *LOP* of the LED with 100-nm-thick pGaN layer increases by 30.9% compared with that of the conventional LED with 300-nm-thick pGaN according to the experimental results. The variable PL measurement results demonstrate that the *LOP* improvement is attributed to the enhancement of the *IQE* of the active layer. The simulation data reveal that the radiative recombination rate and the *IQE* of the LED with 100-nm-thick pGaN are enhanced because of the higher carrier concentrations.

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