The effect of silicon doping in the selected barrier on the electroluminescence of InGaN/GaN multiquantum well light emitting diode

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The effect of silicon doping in the selected barrier on the electroluminescence of InGaN/GaN multiquantum well light emitting diode (LED) was studied using dual wavelength LEDs. The result verified that the hole carrier transport is easily blocked by the silicon doped barrier, and the dominant electron and hole recombination occurs at the wells between *p*-GaN and the silicon doped barrier. The electroluminescence spectrum and the wavelength blueshift of the silicon doped LEDs were compared with undoped LEDs. The numerical simulation was done to clearly explain the hole blocking effect by the silicon doped barrier. © *2006 American Institute of Physics*.
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Despite the high dislocation density (10^8-10^{10} cm^{-2}) and the strong polarization effect, GaN based light emitting diodes (LEDs) have demonstrated relatively high internal quantum efficiency. This is usually explained with the carrier localization effect caused by the indium fluctuation in the quantum well.[1,2] In addition, recent reports[3–6] have suggested that the intentional silicon doping into InGaN-multiquantum well (MQW) seriously affects the optical properties of GaN-based LED. Wu *et al.*[3] reported that the silicon doping in the barrier layers can improve the crystal quality and interfacial qualities of the InGaN/GaN LED. Wang *et al.*[4] reported that an obvious localization effect is found in a slightly Si doped MQW structure, and the stronger localization effect improves the carrier mobility. In addition, there is a report on the Coulomb screening of the piezoelectric field by heavily Si doping.[5]

In this letter, the effect of silicon doing in the selected barrier of InGaN/GaN 5QWs was systemically investigated using five types of dual wavelength LEDs (DW-LEDs). The numerical simulations of an energy band structure and a hole distribution of the selectively silicon doped InGaN/GaN MQW were done to clearly explain the experiment results.

The epitaxial growth was performed using metal organic chemical vapor deposition (MOCVD) with thrimethylgallium (TMGa), thrimethylindium (TMIn), ammonia (NH_3), 150 ppm SiH_4, and bis-cyclopentadienylmagnesium (Cp_2Mg) for gallium, indium, nitrogen, *n*-type and *p*-type dopant precursors, respectively. Epitaxial layers were grown on the *c*-plane sapphire substrates with 0.2° off-cut towards the *m*-plane direction. The LED structure consisted of a 30 nm low temperature buffer layer, a 2 μm unintentionally doped GaN layer, a 2 μm Si doped *n*-type GaN layer ($n = 3\times10^{18}$ cm^{-3}), dual wavelength InGaN (well: 20 Å)/GaN (barrier: 120 Å) five quantum wells (5QWs) active layer, and a 120 nm Mg doped as-grown *p*-type GaN ($p=5\times10^{17}$ cm^{-3}).[7] As shown in Fig. 1(a), the MQW was designed to emit dual wavelengths in order to distinguish the effect of silicon doping. The near dual wavelengths of 470 and 450 nm were chosen for their similar quantum well properties but distinguishable electroluminescence (EL) spectrum. The five InGaN wells were named W1–W5, and the six GaN barriers were named B1–B6 from the *n*-GaN side. The ELs of the DW-LEDs with a 4.2×10^{-4} cm^2 light emission area were measured at a typical forward current, 20 mA.

Reference samples, LED1 and LED2 with undoped DW-MQW, were grown to compare ELs with the silicon doped DW-MQW LEDs. LED1 had four 470 nm wells (W1, W2, W3, and W4) and one 450 nm well (W5). LED2 had three 470 nm wells (W1, W2, and W3) and two 450 nm wells (W4 and W5). The two undoped LEDs showed a dominant EL spectrum peak at 470 nm with a weak shoulder peak at ~450 nm, as shown in Fig. 2(b). The relative intensity of the 450 nm peak was quite small compared to the 470 nm peak due to the dominant electron and hole (EH) recombination at the lower part of the MQW.

The fourth barrier (B4) in LED3 which had the same MQW structure as LED2 was doped with 0.3 SCCM (SCCM denotes cubic centimeter per minute at STP) silicon dopant. The Hall effect measurement of a test sample with the same growth condition as B4 showed a 3.2×10^{18} cm^{-3} electron concentration with a mobility of 150 cm^2/(V s). The EL of LED3, Fig. 1(b), showed a 450 nm wavelength emission without a shoulder at 470 nm. The dominant peak position was shifted from 470 nm (LED2) to 450 nm by the silicon doping of B4. This result implies that the dominant electron and hole recombination occurred at W4 and/or W5, and W1, W2, and W3 did not give any contribution to light emission. In an extreme condition, the fifth barrier (B5) in LED4 which had the same MQW structure with LED1 was doped with the same doping condition. Therefore, LED4 had just one 450 nm well (W5) and four (W1–4) 470 nm wells with the silicon doped B5. However, the EL of LED4 also showed a 450 nm peak wavelength without a 470 nm shoulder, as shown in Fig. 1(b). This result confidently implies that the main light emission came from the W5 which was between the silicon doped barrier and *p*-GaN. LED5 had a silicon

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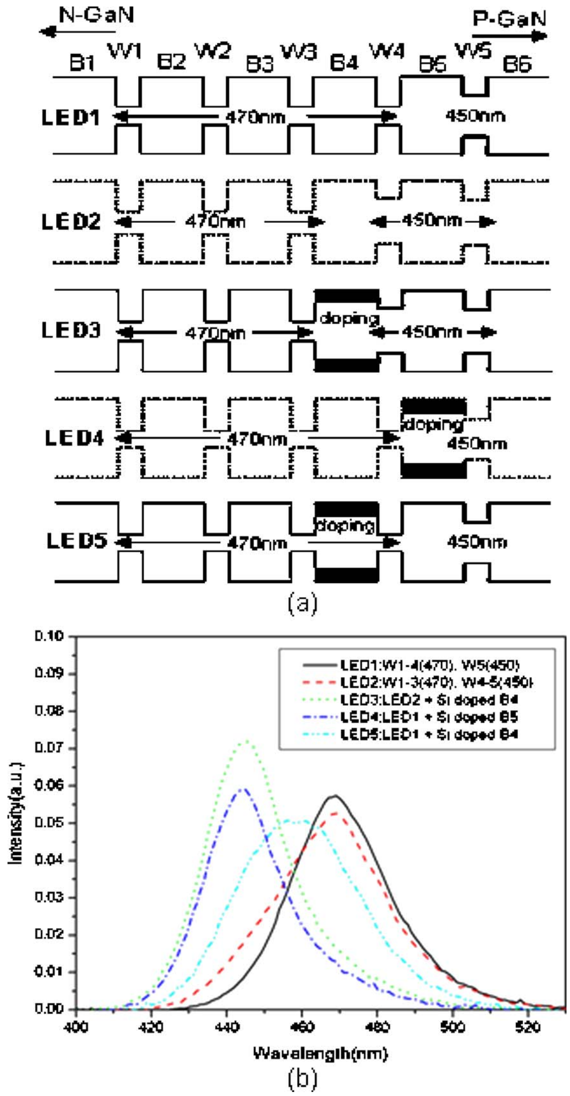

FIG. 1. MQW structures of the five types of DW-LEDs (a) and the ELs of the DW-LEDs at typical operation current, 20 mA (b).

doped B4 barrier with same structure as LED1. Therefore, LED5 had a 470 nm and a 450 nm well between the silicon doped B4 barrier and the p-GaN layer. The EL of LED5, Fig. 1(b), demonstrated a broad spectrum with 42 nm FWHM at $\sim$460 nm center due to the mixed two wavelengths from the W4 (470 nm) and the W5 (450 nm) wells.

Compared with LED1 and LED2 which had the undoped DW-MQW, the strikingly different electroluminescence results of the silicon doped samples verify that the silicon doped barrier can be effectively a hole blocking layer, and a dominant EH recombination occurs at the wells which are placed between the doped barrier and p-GaN. Because hole carriers in the GaN-based material have a high effective mass (hole: $1.1m_0$ electron: $0.2m_0$) and very low mobility ($5-20\ \mathrm{cm^2/V\ s}$), the transport of hole is easily blocked by the pulling down of the energy band of the silicon doped barrier. Figure 2 shows the ELs of LED4 as injection current levels. Although the current was increased up to four times higher than the typical operation current, 20 mA, the EL spectrum showed a slightly increased 470 nm shoulder which comes from the overflow of hole carriers to W1–4. It means that the hole blocking effect by the silicon doped barrier is so effective that almost all the holes are confined in the last well even at the high injection current.

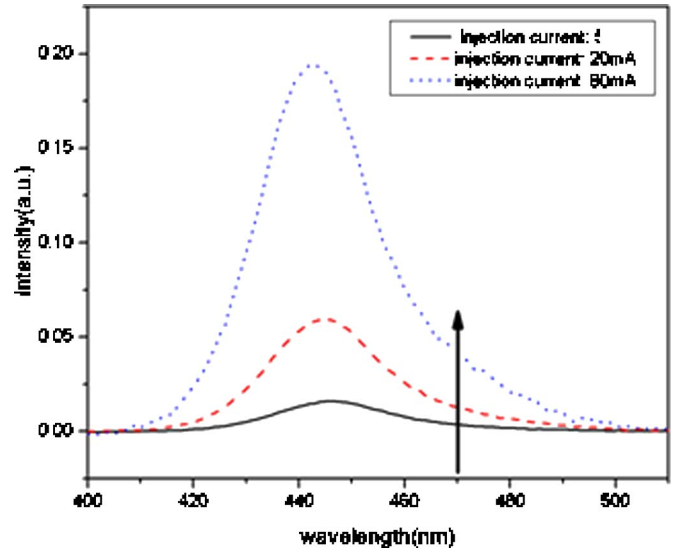

FIG. 2. Electroluminescence spectra of LED4 at injection current levels (5, 20, 80 mA). The arrow indicates the 470 nm shoulder from the quantum wells, W1–4.

The relative optical powers (a.u.) of LED1–5, the average value of 100 chips of each sample, showed 13.5, 13.2, 13.7, 12.3, and 13.4, respectively. The optical power of the LEDs except LED4 demonstrated similar values within run to run error. It means that the silicon doping ($3.2 \times 10^{18}\ \mathrm{cm^{-3}}$) in the selected barrier did not degrade the total radiative recombination rate in the LED. However, the opti-

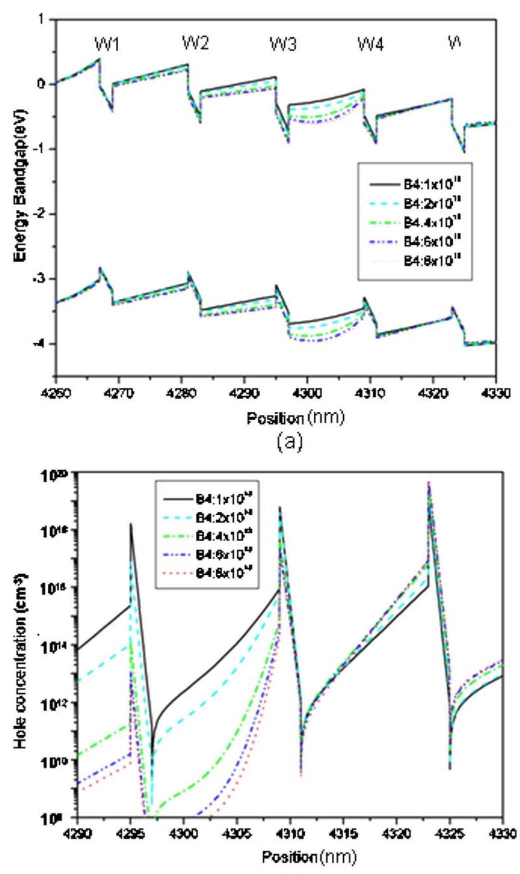

FIG. 3. Simulation results of the energy band diagram (a) and the hole concentration at W3, W4, and W5 (b) of InGaN/GaN 5QWs with a silicon doped ($1, 2, 6, 8 \times 10^{18}\ \mathrm{cm^{-3}}$) barrier, B4.

cal power of LED4 with the doped B5 dropped about 10% compared with the other samples. The power drop of LED4 might come from either the effect of Mg impurity diffusion to W5 or the electron overflow to the *p*-GaN side.

The effect of the selected barrier doping on an energy band and a hole carrier distribution in each of the wells was simulated with a commercial nitride based LED simulator (SiLENSe). In this simulation, electron mobility, hole mobility, and the background doping of the undoped barriers were assumed as $150\ \mathrm{cm^2/(V\,s)}$, $10\ \mathrm{cm^2/(V\,s)}$ and $5\times 10^{16}\ \mathrm{cm^{-3}}$, respectively. The simulations were performed at a typical LED operation forward voltage, 3.4 V, with the LED structure described previously. Figure 3(a) shows the energy band diagram of the InGaN/GaN 5QWs with various silicon doping levels at B4. The energy band of B4 is continuously pulled down at increasing silicon doping level, and finally, the hole barrier height is increased about 0.4 eV more in the mid-$10^{18}\ \mathrm{cm^{-3}}$ silicon doping level. Due to the hole blocking effect by B4, the hole concentration (HC) at W3 is apparently reduced, as shown in Fig. 3(b). With increasing doping level, the HC at W3 is dramatically reduced due to higher hole blocking energy by B4, and the HC at W4 and W5 are relatively increased due to the hole carrier confinement effect. These simulation results clearly explain the hole blocking effect of silicon doped barrier and give a good agreement with the experimental results.

In conclusion, the effect of the silicon doping in the selected quantum barrier was systematically studied using the dual wavelength InGaN/GaN MQW LEDs. The EL results of the DW-LEDs demonstrated that the silicon doped barrier can be a strong hole blocking layer. Consequently, the dominant EH recombination in the silicon doped InGaN/GaN MQW LED occurs at the wells which are between *p*-GaN and the silicon doped barrier. The numerical simulations of the energy band and the hole carrier distribution clearly showed the hole blocking effect, and the results were consistent with the experiment conclusion.

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