Optical properties of a Si delta-doped InGaN/GaN quantum well with ultraviolet emission

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We report on the effect of the position of the Si delta-doped layer within a GaN barrier layer on the optical properties of a InGaN/GaN single quantum well (SQW) with an emission wavelength of 374 nm. When the Si delta-doped layer was very close to the SQW layer, the potential well of the Si delta-doped layer overlapped the SQW potential, reducing photoluminescence (PL) intensity. When the Si delta-doped layer was very far away from the SQW layer, carrier injection from the Si delta-doped layer into the SQW layer was not observed. However, the Si delta-doped layer located 12 nm away from the SQW layer showed enhanced PL intensity due to effective electron injection from the Si delta-doped layer into the SQW layer and to an increase in hole confinement in the valence band. © 2007 American Institute of Physics. [DOI: 10.1063/1.2794714]

I. INTRODUCTION

GaN and related nitrides are among the most promising materials for use in laser diodes and light-emitting diodes (LEDs) in the blue and ultraviolet (UV) regions.1 However, UV LEDs based on InGaN/GaN multiple quantum well (MQW) structures have low internal quantum efficiencies due to poor confinement of carriers by the small band offset between the InGaN well layer and the GaN barrier layer. This effect has been attributed to the low In content of InGaN QW layers2 and also to the lack of In-rich regions, which provide deep potential wells that suppress diffusion of electrical carriers toward various nonradiative defects.3–5 Therefore, it is necessary to improve internal quantum efficiency of UV LEDs by increasing carrier injection into the quantum well (QW) layer and carrier confinement in the InGaN/GaN MQW structures. Recently, we reported that the insertion of Si delta-doping layers within the GaN barrier layer of MQW improved the efficiency of an InGaN/GaN UV LED.6 When Si delta doping was introduced into the middle of the MQW barrier layer, photoluminescence (PL) intensity of the MQW and output power of the UV LED improved. However, the effect of the position of the delta-doped layer within the barrier layer of the QW structure on the efficiency of electron injection and on carrier confinement is not clearly understood. In this study, the effects of the position of the Si delta-doped layer within the GaN barrier layer of a single quantum well (SQW) on the optical properties of an InGaN/GaN UV SQW with an emission wavelength of 374 nm were examined.

II. EXPERIMENT

The structure of InGaN/GaN SQW is shown in Fig. 1. The InGaN/GaN SQW was grown on a (0001) sapphire substrate using a metal organic chemical vapor deposition (MOCVD) system. The substrate was initially treated with H₂ at a temperature of 1050 °C, followed by growth of a 25-nm-thick, low temperature GaN buffer layer at 550 °C. After high temperature annealing of the buffer layer, a 2-μm-thick undoped GaN layer and 2-μm-thick n-type GaN layer were grown at 1040 °C. An InGaN/GaN SQW that consisted of two 20-nm-thick GaN barrier layers and a 2-nm-thick InGaN well layer was subsequently grown at a low temperature of 800 °C. Si delta doping was introduced into both layers of the GaN barrier, equidistant from the InGaN SQW layer. The procedure for growing a Si delta-
III. RESULTS AND DISCUSSION

To confirm the formation of a Si delta-doped layer within the GaN barrier, capacitance-voltage (C-V) was measured at the room temperature. As shown in the inset of Fig. 2(a), the sample for the C-V measurement consisted of a 25-nm-thick low temperature GaN buffer, a 2-μm-thick undoped GaN layer, and a 2-μm-thick n-type GaN:Si layer. This was followed by growth of a 40-nm-thick GaN layer at 800 °C which was the same temperature as that for growth of the GaN barrier layer of SQW. Then, the Si delta-doping process was performed on the GaN surface. After the Si delta-doping process, a 10-nm-thick GaN layer was deposited. Then, the growth temperature was increased to 1040 °C and a 100-nm-thick GaN layer was grown on top of the 10-nm-thick GaN layer. This was done to confirm the doping profile of the Si delta-doped layer within the GaN barrier layer grown at a high temperature (1040 °C), which normally is used to grow a p-GaN layer. After sample growth, a Schottky metal contact with a size of 100 nm² was fabricated by e-beam evaporation of gold. Aluminum was then deposited on the perimeter of the sample surface to serve as an Ohmic contact. A C-V profile was performed on the sample at room temperature, as shown in Fig. 2(a), to measure the doping density profile. The C-V profile shows two peaks, indicating that carriers are accumulated in two regions. The first accumulation layer (region 1) can be formed by defects, such as nitrogen vacancies and carriers localized at the interface between the GaN layer grown at low temperature (800 °C) and that grown at high temperature (1040 °C). The second peak (region 2) shows that the carriers are localized in the Si delta-doped layer. Figure 2(a) shows that the doping density of the Si delta-doped layer is 3.8 × 10¹⁹ cm⁻³ and its full width at half maximum (FWHM) of the C-V profile peak is 3.5 nm. The doping concentration is increased linearly with the SiH₄ flow rate. These results indicate that a Si delta-doped layer is formed within the GaN barrier layer of the SQW, as shown in Fig. 2(b).

The effect of the position of the Si delta-doped layer within the barrier layer of SQW on the PL properties of InGaN/GaN SQW is shown in Fig. 3. The PL measurement was carried out using a He–Cd laser of 325 nm at the room temperature. The distance between the Si delta-doped layer and SQW layer are 4, 8, 12, and 16 nm for samples A–D, respectively. The peaks around the main PL peak can be resulted from the two origins. First, the small periodic peaks around 368 and 379 nm are due to Fabry-Pérot interference by internal multiple reflection at the surface and at the n-GaN and sapphire interface of the InGaN SQW structure. Secondly, the peaks around 368 nm are also originated from the carrier transition between the delta-doped layer and the valence band of the InGaN layer. This will be further discussed in Fig. 5. As the distance between the Si delta-doped layer and SQW layer increased from 4 to 12 nm, the PL in-
tensity also increased, as shown in Fig. 3(a). However, when the distance between the Si delta-doped layer and SQW layer was 16 nm, the PL intensity significantly decreased. Figure 3(a) shows that, when the Si delta-doped layer is too close to the SQW layer, the PL intensity becomes weak. Previous reports indicated that a Si delta-doped layer provided a potential well for electrons in the conduction band and a potential barrier for holes in the valence band. This suggests that the potential well of the Si delta-doped layer is overlapped with the potential of InGaN SQW, decreasing confinement of electrons in the InGaN quantum well, as shown in sample A in Fig. 3(b). On the other hand, when the Si delta-doped layer is too far away from the SQW layer, as shown in sample D in Fig. 3(b), the injection of electrons from the Si delta-doped layer into the SQW layer significantly decreases, reducing PL intensity, as shown in Fig. 3(a). Figure 3(a) also shows that the PL spectra blue shift when the distance between the Si delta-doped layer and SQW layer is increased (from sample A to sample C) and then redshift as the distance is increased further (sample D). The blueshift was attributed to the screening of a piezoelectric field induced by the strain in the InGaN SQW resulting from lattice mismatch between the InGaN and GaN layers. It was reported that, when the carrier density was increased in the QWs, a screening of the piezoelectric field induced a blueshift in the PL peak of the QWs. The screening effect is dependent on the concentration of electrons confined in the SQW by a band offset of conduction bands and by efficient electron injection from the Si delta-doped layer into the SQW layer. Therefore, as the distance increased from 4 to 12 nm, the number of electrons increased in the SQW layer due to effective electron injection from the Si delta-doped layer, resulting in a blueshift of the PL peak. However, the PL peak was redshifted as the distance between the Si delta-doped layer and SQW layer was further increased. This phenomenon is attributed to a decrease in the number of electrons in the SQW layer, resulting from diminished injection of electrons from the Si delta-doped layer to the SQW layer.

Figure 4 shows an Arrhenius plot of the normalized, integrated PL intensity of PL spectra of samples A–D in the temperature range of 10–200 K. The activation energy of the thermally activated process can be estimated using the following equation:

\[ I(T) = \frac{I_0}{1 + A \exp(-E_{a1}/K_B T) + B \exp(-E_{a2}/K_B T)}, \]

where \( I(T) \) is the temperature-dependent integrated PL intensity, \( I_0 \) is the integrated PL intensity at low temperatures, \( K_B \) is Boltzmann’s constant, and \( A \) and \( B \) are rate constants. Note that \( E_{a1} \) represents the exciton binding energy of InGaN QW in the temperature range of 40–70 K and \( E_{a2} \) represents the activation energy for thermal emission of carriers out of confining potentials correlated with the depth of the confining potentials above the temperature of 70 K. The Arrhenius fitting showed that the \( E_{a1} \) for samples A–D were 12.6, 17.2, 18.0, and 10.3 meV, respectively, and \( E_{a2} \) increased with increasing the distance between the Si delta-doped layer and SQW layer. The strain-induced piezoelectric field of the SQW layer within this study (1.2 MV/cm for a similar MQW with undoped barrier) is larger than the classical exciton ionization field of 1.1 MV/cm (=E_B/ea_B), where \( E_B \) is the zero-field exciton binding energy of 22 meV and \( a_B \) is the exciton Bohr radius of 2 nm in GaN. Therefore, the piezoelectric field can separate the electron-hole pairs and drastically reduces their overlap integral at low carrier density, resulting in a reduction of exciton binding energy of \( E_{a1} \). As the distance between the Si delta-doped layer and SQW layer was increased to 12 nm, the carrier concentration in the QW layer is increased due to higher electron injection as shown in Fig. 3(b). Therefore, the oscillator strength of excitons is increased by screening of the piezoelectric field by excess carriers. However, \( E_{a1} \) decreased at a distance of 16 nm. This is attributed to a decrease in screening of piezoelectric field by reduced injection of electrons from the Si delta-doped layer into the SQW layer. The \( E_{a2} \) for samples A–D were estimated to be 34.4, 48.2, 52.5, and 35.0 meV, respectively. When the distance between Si delta-doped layer and SQW layer is 4 nm, \( E_{a2} \) is at its minimum because the potential well of the Si delta-doped layer overlaps with the potential of InGaN SQW, decreasing the confinement of carriers, as shown in Fig. 3(b). When the distance between Si delta-doped layer and SQW layer is increased to 12 nm, \( E_{a2} \) increases due to a decrease in overlapping potentials of the InGaN SQW and of the Si delta-doped layer in the conduction band. As the distance between the Si delta-doped layer and SQW layer is further increased, \( E_{a2} \) decreases due to reduced confinement of holes in the valence band.

Figures 5(a) and 5(b) show the temperature-dependent PL spectra of samples C and D, respectively. Sample C showed two dominant peaks (I_1 and I_2) while sample D showed only one dominant peak (I_2). Figure 5(c) shows a band diagram, illustrating the origin of the two peaks (I_1 and I_2) in samples A and C. The excited energy level in the delta-doping layer with a V-shaped electrostatic potential was calculated to be 145 meV, by using the Dirac delta function and the Poisson equation. The PL peak on the high energy side (I_1) results from the carrier transition between the delta-doped layer and the valence band of the InGaN layer. The

![Figure 4](image-url)
transition. When the Si delta-doped layer is too far away from the QW layer (sample D), only the $I_2$ peak is observed due to the lack of interaction between the two potentials, as shown in Fig. 5(a). Therefore, the $I_2$ peak of sample D decreased faster than that of sample C, as shown in Fig. 5(b).

**IV. CONCLUSION**

The effect of the position of the Si delta-doped layer within a GaN barrier of InGaN/GaN SQW with a UV emission of 374 nm on optical properties was studied. When the Si delta-doped layer was very close to the SQW layer (4 nm), the potential well of the Si delta-doped layer overlapped with the SQW potential, resulting in a reduction in PL intensity. On the other hand, when the Si delta-doped layer was very far away from the SQW layer (16 nm), carrier injection from the Si delta-doped layer into the SQW layer was not observed. However, the Si delta-doped layer located at a distance of 12 nm from the SQW layer strongly enhanced PL intensity due to effective carrier injection from Si delta-doped layer into the QW layer and higher carrier confinement.

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