Photoluminescence and electrical characteristics of the two-dimensional electron gas in Si delta-doped GaN layers

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We have studied the electrical and photoluminescence (PL) properties of a Si delta-doped GaN layer grown by metalorganic chemical vapor deposition. The Hall mobility and electron sheet concentration are 726 cm^2/V s and 1.9×10^{12} cm^{-2}, respectively, at 2 K. A PL peak located at 78 meV below the band gap of GaN is observed at 77 K. This PL peak is attributed to the radiative recombination between electrons in the two-dimensional quantum states and photoexcited holes in GaN, which is consistent with simulation results using a one-dimensional Poisson and Schrödinger equation solver. The peak disappears at temperatures higher than 77 K and is not observed in uniformly doped GaN layers. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1353836]

Delta doping of GaAs and other compound semiconductor structures has been intensively studied in the past decade. Confining the dopants to a single or few monolayers of the semiconductor lattice allows one to explore the fundamental aspects of device physics and to fabricate device structures such as delta-doped metal–semiconductor field-effect transistors and *n-i-p-i* superlattices.[1] Recent development of high-power and high-speed electronic devices based upon Al$_x$Ga$_{1-x}$N/GaN heterostructures is very promising because of their large band gap energy, high electron peak velocity, and high breakdown electric field.[2,3] Applying the delta doping technique in III-nitride based high-speed transistor fabrication is especially interesting. Kim *et al.* recently reported a sharp carrier concentration profile with a peak concentration 9.8×10^{18} cm^{-3} by measuring the capacitance–voltage characteristics on Si delta-doped GaN layers grown by metalorganic chemical vapor deposition.[4] So far, however, there has been no report on the electrical or optical properties of delta-doped GaN layers.

Low-temperature photoluminescence (PL) related to the radiative recombination between the two-dimensional electron gas (2DEG) and photoexcited holes have been useful tools in understanding the quantum confined states of 2DEG at Al$_x$Ga$_{1-x}$As/GaAs heterointerfaces[5,6] and in delta-doped GaAs layers.[7] Recently, PL studies of the 2DEG have been extended to Al$_x$Ga$_{1-x}$N/GaN heterostructures. For example, Bergmann *et al.* reported that a broad weak PL peak about 50 meV below the free exciton emission of GaN and interpreted it as arising from the recombination of electrons within the 2DEG at the Al$_x$Ga$_{1-x}$N/GaN heterointerface with photoexcited holes in GaN.[8] Kwon *et al.* also identified

a 4 K PL peak due to the radiative recombination between the 2DEG and holes bound to residual acceptors.[9] Shen *et al.*, however, found that the intensity of the 2DEG peak could be enhanced significantly by incorporating a thin Al$_{0.12}$Ga$_{0.88}$N layer in the GaN layer near the heterointerface to suppress the diffusion of photoexcited holes.[10] In this letter, we report results from a PL study of delta-doped GaN layers. A PL peak located at 78 meV below the band gap of GaN is observed at 77 K and is attributed to the recombination between 2DEG and photoexcited holes in GaN.

The Si delta-doped GaN layers were grown by metalorganic chemical vapor deposition using triethylgallium in combination with ammonia, silane, and a H$_2$ diluent. A 100-nm-thick AlN buffer layer was first grown on an on-axis 6H-SiC(0001) substrate at 1100 °C. This was followed by the growth of an ~1 μm unintentionally doped GaN layer, a 7.5-nm-thick Si doped GaN layer, and then a 0.1 μm GaN capping layer at 1000 °C. The Si dopant concentration was estimated to be 1×10^{19} cm^{-3}. It has been shown that Si can change the growth mode of GaN.[11] However, cross-sectional transmission electron microscopy measurements revealed no change in the growth mode and a relatively low dislocation density in the sample, which is consistent with the PL data shown later. The mobility of the Si delta-doped GaN layers was investigated using Hall measurements in a Van der Pauw configuration at various temperatures and the results are shown in Fig. 1. The ohmic contacts to GaN were made of Au and Al alloyed at 480 °C. The Hall mobility and electron sheet concentration are 726 cm^2/V s and 1.9×10^{12} cm^{-2}, respectively, at 2 K. The Hall mobility decreases with increasing temperature, reaching a value of only 15 cm^2/V s at room temperature, which is much lower than the values reported by Götz *et al.*[12] on uniformly doped GaN layer with Si concentration of ~2×10^{19} cm^{-3} grown by

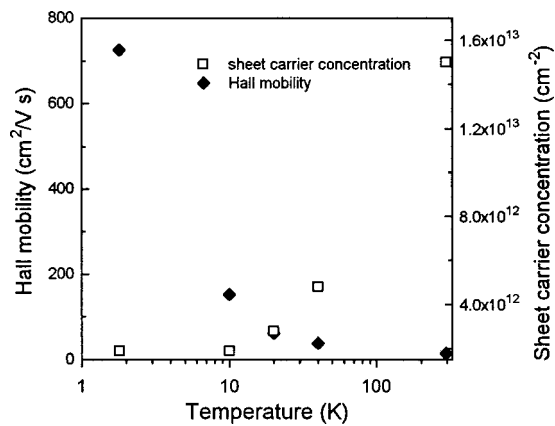---

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FIG. 1. The Hall mobility and sheet carrier concentration of a Si delta-doped GaN layer as a function of temperature.

metalorganic vapor phase epitaxy. The low room-temperature mobility may be attributed at least in part to scattering by ionized impurities or charged defects created during the growth. Nevertheless, the behavior observed here is very similar to that found in $Al_xGa_{1-x}N/GaN$ heterostructures. However, it is markedly different from the results reported in Ref. 12 for uniformly doped samples, which show that the mobility reaches a peak value of 135 cm^2/V s at 300 K and then decreases as the temperature is lowered.

The PL spectra were excited at 77 K with a continuous-wave argon ion laser (270–305 nm) and collected using a 0.64 m spectrometer equipped with an S-20 photocathode. In Fig. 2(a) we show the PL spectrum from a Si delta-doped GaN layer. The PL spectrum from a uniformly doped GaN layer with Si concentration of $\sim 5 \times 10^{17}$ cm^{-3} (~ 1 μm thick) is also shown in Fig. 2(b) for comparison. The dominant band edge emission (~ 360 nm) and a set of deep level emission peaks at 380, 391, and 403 nm are observed in both samples. The full width at half maximum of the band edge emission in the delta-doped sample is approximately 12 meV, indicating very high crystal quality of the layer. In both samples, the peak at 380 nm is identified as due to donor-shallow-acceptor pair (DAP) recombination.[13,14] Two LO-phonon replicas (391 and 403 nm) at intervals of 92 and 185 meV were observed at 77 K due to the electron-phonon coupling of the DAP transitions. A relatively weak emission peak at 366.8 nm (3.379 eV), 78 meV below the band edge, is only observed in the delta-doped GaN sample. This peak, however, was not observed when the temperature was raised to higher temperature.

To understand the origin of this peak, the structure was simulated using a one-dimensional Poisson and Schrödinger equation solver.[15] In the modeling we assumed a 7.5-nm-thick delta-doped region with Si concentration of 1×10^{19} cm^{-3} sandwiched between undoped GaN layers with residual donor concentration of 1×10^{15} cm^{-3}. The electron and hole effective masses used in the simulations are 0.20 and 1.80 m_0, respectively. The simulated band diagram of the delta-doped sample is shown in the inset of Fig. 2(a). The Fermi level (E_F) of the system at equilibrium is 25 meV below the unperturbed GaN conduction band edge, and the ground quantum confined state energy of the 2DEG is ~ 53 meV below the Fermi level. The transition energy of the radiative recombination between the 2DEG and free holes at
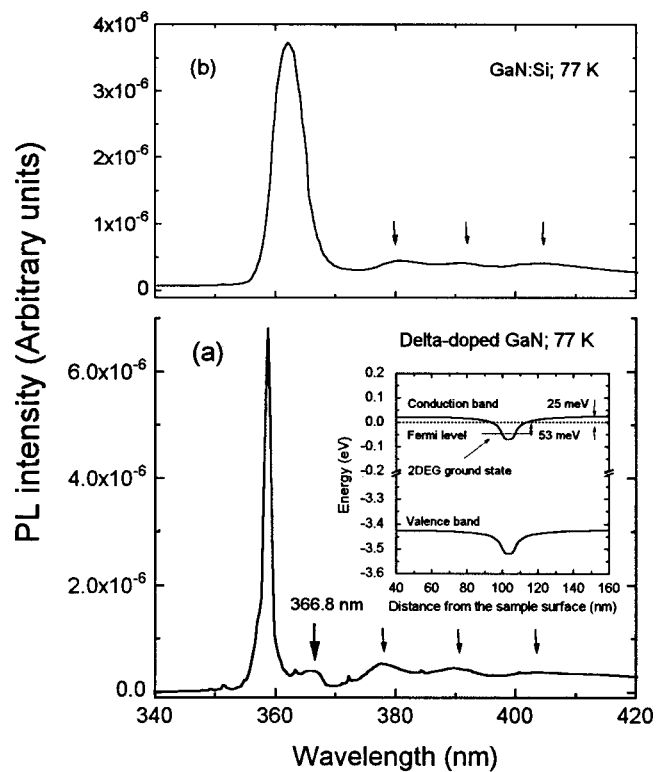

FIG. 2. (a) The PL spectrum of a Si delta-doped GaN layer measured at 77 K. The arrow at 366.8 nm designates the radiative recombination between electrons in the 2DEG and photoexcited holes. The other three arrows designate the donor-acceptor-pair recombination and its LO-phonon replica. The simulated band diagram of the delta-doped sample by using a one-dimensional Poisson and Schrödinger equation solver is shown in the inset. (b) The 77 K PL spectrum of a uniformly Si-doped GaN sample.

the valence band edge is therefore 78 meV below the band gap of GaN, which is consistent with our PL results. The uncertainties in the transition energies as a result of ±10% fluctuation of dopant concentration or delta-doped layer thickness are only ±4 and ±2 meV, respectively, which are within the experimental error range. The effective electric field in a delta-doped structure can be calculated by considering a V-shaped quantum well in the region. The eigenstate energies of a V-shaped quantum well can be solved analytically by using Wentzel–Kramers–Brillouin approximation and are given by[1]

$$E_n = \left[\frac{3}{4}\left(n+\frac{1}{2}\right)\right]^{2/3}\left(\frac{e^2\hbar^2F^2}{2m_e^*}\right)^{1/3} \quad n = 0, 1, 2..., \quad (1)$$

where F is the effective electric field, and E_n is the nth eigenstate energy of 2DEG relative to the bottom of the well. From the simulation the ground state energy is ~ 16 meV above the bottom of the well, and the effective electric field is calculated to be 3.1×10^4 V/cm, which is close to the field value in $Al_xGa_{1-x}N/GaN$ heterostructures reported in Ref. 9.

It is interesting to verify the origin of the 366 nm emission peak from the delta-doped GaN sample by comparing the low temperature PL results with those from $Al_xGa_{1-x}N/GaN$ heterostructures.[9,10] We therefore performed PL measurements on an $Al_{0.12}Ga_{0.88}N/GaN$ single heterostructure sample at 77 K. The sample is grown on a 6H-SiC substrate. From the bottom to the top, it consists of a 100 nm AlN buffer layer, a 1.2-μm-thick undoped GaN layer, a 10-nm-thick $Al_{0.12}Ga_{0.88}N$ spacer, a 170-nm-thick
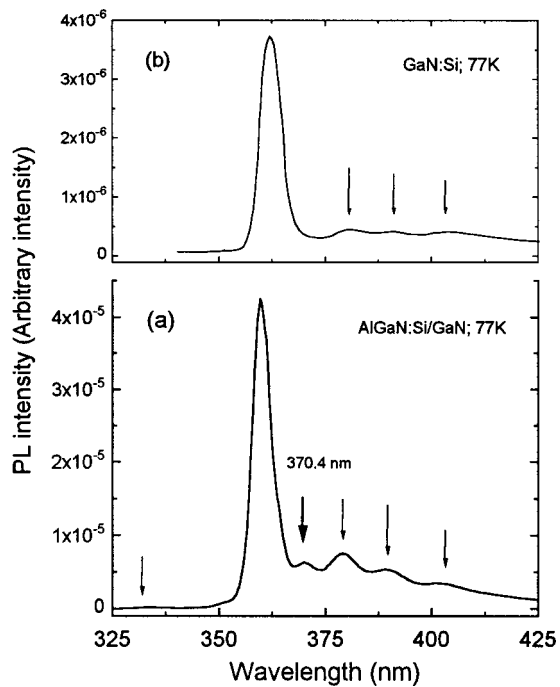
FIG. 3. (a) The PL spectrum of a doped $Al_{0.12}Ga_{0.88}N/GaN$ heterostructure at 77 K. (b) The PL spectrum of a uniformly Si-doped GaN sample at 77 K.

n-$Al_{0.12}Ga_{0.88}N$:Si(1×10^{19}/cm^3), and then capped with a 70-nm-thick GaN:Si layer. The fact that the 2DEG were formed at the heterointerface was verified by Hall mobility measurements. The PL spectrum for this heterostructure sample is shown in Fig. 3(a). Similarly, the dominant band edge emission (361.2 nm) and a set of deep level emission peaks are observed in the uniformly Si-doped GaN [Fig. 3(b)] and the $Al_xGa_{1-x}N/GaN$ heterostructure. A weak peak at ~330 nm is observed and assigned to the emission from the $Al_{0.12}Ga_{0.88}N$ layer. The 370.4 nm peak is only observed in the heterostructure sample and is similar to the PL peak reported by Kwon *et al.* (Ref. 9) on a modulation-doped $Al_{0.37}Ga_{0.63}N/GaN$ single heterostructure. As in Ref. 9 we assume the transition results from the radiative recombination of electrons in the 2DEG with holes weakly bound to residual acceptors in GaN. This suggests that low-temperature PL is a very sensitive tool to explore the quantum confined states of 2DEG in delta-doped GaN layers and modulation-doped $Al_xGa_{1-x}N/GaN$ heterostructures.

In summary, the electrical and PL properties of a Si delta-doped GaN layer grown by metalorganic chemical vapor deposition were investigated. The Hall mobility and electron sheet concentration are 726 cm^2/V s and 1.9×10^{12} cm^{-2}, respectively, at 2 K. A PL peak located at 78 meV below the band gap of GaN is observed at 77 K, and is attributed to the radiative recombination between electrons in the two-dimensional quantum states and photoexcited holes. A comparative study was performed on uniformly Si-doped GaN and $Al_xGa_{1-x}N/GaN$ heterostructures to verify that the luminescence is indeed related to the two-dimensional electron states. The experimental results are consistent with those from simulations using a one-dimensional Poisson and Schrödinger equation solver.

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