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Extremely Sharp Photoluminescence Lines from Nitrogen Atomic-Layer-Doped AlGaAs/GaAs Single Quantum Wells

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Abstract

We have performed nitrogen atomic-layer-doping into AlGaAs/GaAs single quantum wells for the first time. The single quantum wells show sharp photoluminescence lines at 8 K. These lines are observed at longer wavelength than those obtained for undoped single quantum wells, indicating that they correspond to the excitons bound to nitrogen atoms in the quantum wells. The binding energy of excitons increases with the substrate temperature during doping.

1. Introduction

Nitrogen (N) atoms act as isoelectronic traps in GaP and the photoluminescence (PL) lines related to these N atoms are very sharp.[1] While there have been many studies on the PL characteristics of N-doped GaP, there are few on N-doped GaAs, which is a direct gap semiconductor. It has been predicted that N induced states are not formed within the GaAs band gap.[2] Wolford *et al.* observed that N doping induced a "deep-trap resonance" above the GaAs band edge, which was driven into the fundamental gap under hydrostatic pressure.[3]

However, under no hydrostatic pressure conditions, Schwabe *et al.* observed for the first time sharp PL lines corresponding to excitons bound to N atoms for uniformly N-doped GaAs (6×10^{17} cm^{-3}) layers grown by vapor phase epitaxy using NH_3 as the doping source.[4] This is thought to be due to a large symmetry change around N atoms from the tetrahedron because of the large difference in bond lengths between Ga-As and Ga-N bonds. Recently, we have reported that N atomic-layer-doped (N-ALD) GaAs layers grown by molecular beam epitaxy (MBE) show sharp lines from excitons trapped by N atoms with higher binding energies.[5] In this conference, we will discuss the PL characteristics of N-ALD AlGaAs/GaAs single quantum wells (SQWs).

2. Experiment

GaAs and $Al_{0.33}Ga_{0.67}As$ layers were grown by MBE at 590 °C on (001) semi-insulating GaAs substrates. The structures were doped with N using N_2 molecules cracked by a tungsten filament.[6] With this method, the N-doping concentration can be controlled precisely by adjusting the filament temperature and/or N_2 flow-rate. Figure 1 shows the structure of a N-ALD AlGaAs/GaAs SQW. The N-ALD layer was inserted at the center of a GaAs well in this SQW. Undoped GaAs, AlGaAs buffer layers, and half of a GaAs SQW were grown first. After stopping the Ga and As fluxes, atomic-layer-doping was performed using a N_2 flow through the hot W filament on the surface. Then, the rest of the GaAs SQW, undoped AlGaAs barrier and GaAs cap layers were regrown. For PL measurements at 8 K, we used an Ar laser operating at 488 nm with an excitation power density of 0.1 W/cm^2 and a double monochrometer with the spectra resolution of 0.1 meV. The well width (L_w) and the substrate temperature during the N-doping were changed. In this experiment, the sheet N density was fixed and estimated at 1×10^9 cm^{-2} because the N-ALD GaAs layer with a sheet N density of 1×10^9 cm^{-2} shows a series of sharp and strong PL lines. The N atom concentrations in N-doped GaAs layers were determined using secondary ion mass spectrometry (SIMS). However, for lower N atom concentrations below the detection limit of SIMS (5×10^{16} cm^{-3}), we estimated the concentration from the activation energy (3.6 eV) of the cracking efficiency by the hot W filament.

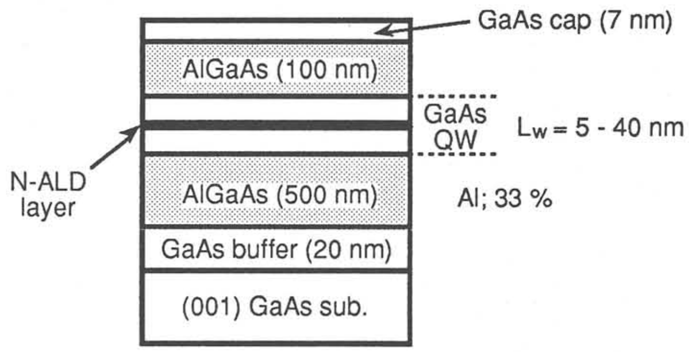

Fig. 1. Structure of a N-ALD AlGaAs/GaAs SQW

3. Results and discussions

Figure 2 shows PL spectra for AlGaAs/GaAs SQWs doped with N atoms at 480 °C. The well widths are 20, 10, and 5 nm. The arrows indicate the peak positions of the luminescence from the reference QW samples without the N-ALD layer. In all PL spectra, the luminescence from the QW itself disappears and PL lines are observed at a longer wavelength than those obtained for undoped single quantum wells. These lines correspond to the excitons bound to N atoms as isoelectronic traps in the quantum wells. The radiative recombination lifetime of these excitons is much smaller than that of excitons in a SQW at low temperatures. In the PL spectrum of the N-ALD SQW with L_w of 20 nm, a strong and dominant PL line relating to N atoms appears at a wavelength of 821 nm. Its full width at half maximum (FWHM) is 0.3 meV. The peak wavelength changes a little (2.2 meV) as L_w decreases from 20 nm to 10 nm, suggesting that the excitons are localized around N atoms at the center of the QW. Figure 3 shows FWHM values for N-ALD AlGaAs/GaAs SQWs as a function of L_w. For comparison, FWHM values for undoped SQWs are also shown. Above 10 nm, the FWHM values for N-ALD SQWs are much smaller than those for undoped SQWs. These FWHM values are independent of L_w above 10 nm for N-ALD SQWs, while the monolayer thickness fluctuation of L_w makes the FWHM values increase with a decrease in L_w for undoped SQWs. This also suggests that the excitons are localized around N atoms in N-ALD SQWs. However, the PL lines are drastically broadened for L_w of 5 nm in N-ALD SQW, indicating that excitons trapped at the N atoms are modulated by the thickness fluctuation of L_w due to a well width narrower than the exciton diameter.

Next, L_w is fixed at 20 nm, while the substrate temperature during the N-doping is changed. Figure 4 shows PL spectra for SQWs doped with N at 480, 530 and 590 °C. Three strong and sharp lines are observed at 821, 838, and 860 nm. These intensities strongly depend on the temperature. Figure 5 shows PL intensities of three N-related lines as a function of the substrate temperature. As the temperature increases, PL peaks of longer wavelengths become dominant, indicating that the binding energy of excitons increases with the substrate temperature. The substrate temperature might affect the incorporation sites of N atoms or the formation of N pairs.

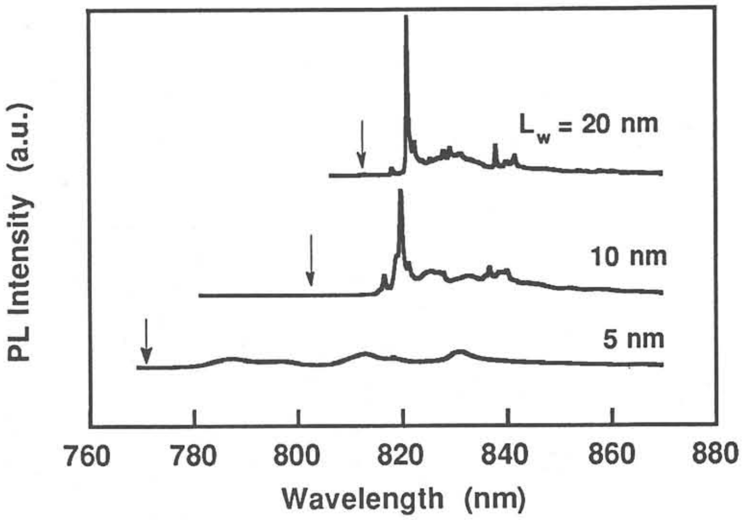

Fig. 2. PL spectra for N-ALD AlGaAs/GaAs SQWs for different well widths. The well widths are 20, 10, and 5 nm. The arrows indicate the peak positions of the luminescence from the reference QW samples without the N-ALD layer.

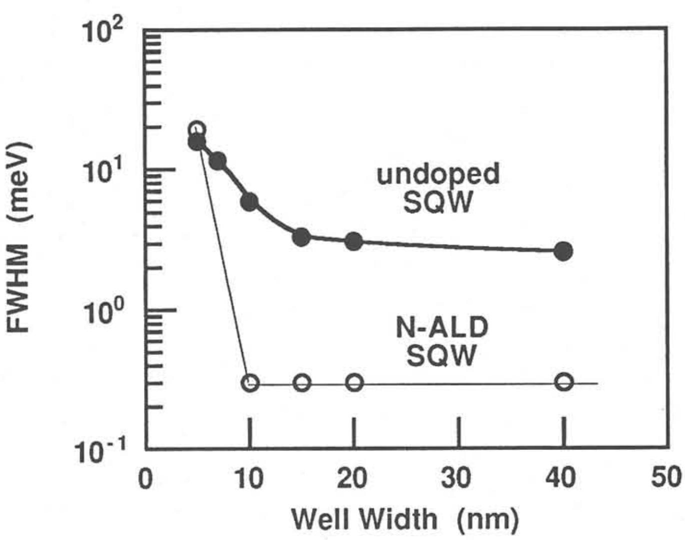

Fig. 3. FWHM for N-ALD AlGaAs/GaAs and undoped SQWs as a function of L_w.

4. Conclusion

We have grown N-ALD AlGaAs/GaAs SQWs using N_2 cracked by a hot W filament and investigated their PL characteristics. Sharp lines were observed with FWHM of 0.3 meV, which corresponded to the excitons bound to nitrogen atoms as isoelectronic traps in the quantum wells. The peak wavelength changed a little and FWHM was independent of L_w above 10 nm for N-ALD SQW, suggesting that the excitons were localized around N atoms. The PL lines were broadened, however, for L_w of 5 nm in N-ALD SQW. This suggests that excitons trapped at the N atoms are modulated by the thickness fluctuation of L_w due to a well width narrower than the exciton diameter. As the substrate temperature during doping increased, PL peaks of longer wavelengths became dominant, indicating that the binding energy of excitons increases with the temperature.

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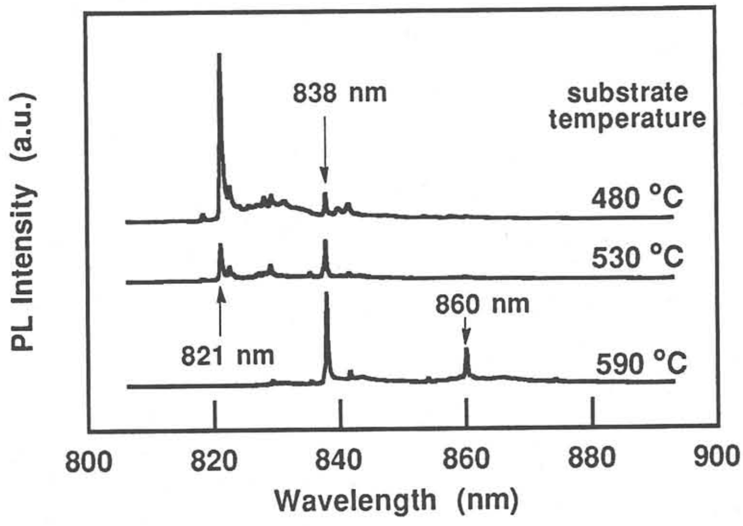

Fig. 4. PL spectra for SQWs doped with N at three substrate temperatures.

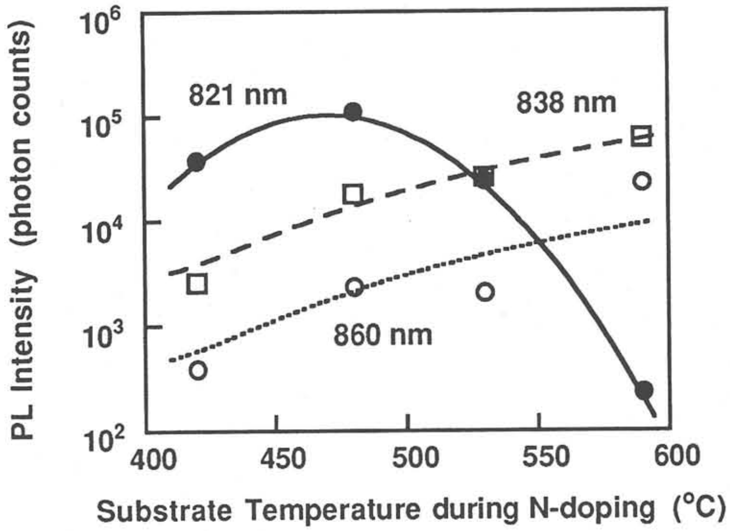

Fig. 5. PL intensities of N-related lines as a function of substrate temperature.