Effect of Silicon Doping in GaAs$_{1-x}$N$_x$/GaAs Quantum Well Observed by Photoluminescence Measurement

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Abstract: In this work, we report the experimental results on the effect of silicon in low-temperature photoluminescence spectra (LTPL) of a set of GaAs$_{1-x}$N$_x$/AlGaAs heterostructure with modulation doped. These samples were grown on (001) oriented GaAs substrates by molecular beam epitaxy (MBE) with different nitrogen composition. The Si-doped effect has been analyzed by photoluminescence (PL) measurements. At low power excitation density the PL spectra of undoped quantum wells (QW) are formed by GaAsN band level and several features attributed to the nitrogen localized states. For the Si-doped quantum wells, the GaAsN band level disappears and the large band attributed to the nitrogen localized states changes the form. At high power excitation density, the PL spectrum is formed by only one peak corresponding to the most dominating nitrogen localized state. With comparison between the doped and undoped QWs, we note that the presence of silicon in the structure reduce the exciton bound energy to the nitrogen localized states.

Key words: GaAsN, Molecular beam epitaxy, power excitation, Photoluminescence spectroscopy, Si-doping.

INTRODUCTION

The dilute group III-AsN materials system, on-GaAs with a nitrogen content $y$ in the few percent range, has attracted considerable current interest, for their fundamental properties and for their promising optoelectronic applications [1–6]. The incorporation of nitrogen leads to many interesting physical properties such as a strong redshift of the band gap energy, creation of localized states, etc. [7–10]. In this work, we report low-temperature photoluminescence (LTPL) studies of silicon doping effect on GaAs$_{1-x}$N$_x$ QW with low nitrogen composition $[N] = 2 \times 10^{18}$cm$^{-3}$.

1. Experimental details

The two studied samples Si-doped and undoped QWs were grown by molecular beam epitaxy (MBE) system on (001) GaAs oriented substrates. The sample 1 is formed by a 100 nm GaAs$_{1-x}$N$_x$ (Si) channel and two spacer layers: a 3 nm GaAs and a 1 nm AlGaAs undoped spacer. The GaAs spacer is introduced to prevent a possible interaction between Al and N. Finally, 3 nm GaAs cap layer complete the structure.

2. Results and discussion

The sample 2 is similar that sample 1 but without Si in the quantum well. Figure 1 shows the
photoluminescence spectra of the two samples Si-doped and undoped QWs at low temperature T=10 K under an excitation power of 0.5 Wcm⁻².

Fig. 1: 10 K normalized photoluminescence spectra of GaAsₓN₁₋ₓ and GaAsₓN₁₋ₓ(Si) depicting the influence of doping with silicon at 0.5 W.cm⁻².

For the undoped sample, the PL spectra is essentially formed by a fine structure at 1.516 eV attributed to GaAs transition and a low energy wide band which attributed to the nitrogen localized states as NNA, NNB, NND and NN₁. For the doped sample, the intensity of GaAs transition decreases strongly and the low energy wide band becomes more widened and the fine structures of nitrogen localized states at 1.430, 1.448, 1.473 and 1.485 eV corresponding respectively to NN₁, NND, NNA and NN₁ become more pronounced. The origin of those features has been clarified recently by Saito et al. [11] and Francoeur et al. [12]. Photoluminescence measurements as function of power excitation have been carried out in figure 2.

Fig. 2: 10 K normalized photoluminescence spectra of GaAsₓN₁₋ₓ and GaAsₓN₁₋ₓ(Si) depicting the influence of doping with silicon at 4 W.cm⁻².

We note that for high power excitation corresponding to 4 Wcm⁻², PL spectra of undoped and doped QW’s change the form and the PL maximum become respectively at 1.45eV and 1.48 eV corresponding to NN₁ and NN₁ features. Figure 3 shows the PL integrated intensity of Si-doped (Fig.3a) and undoped (Fig.3b) QWs as function of laser power excitation for three temperatures 10 K, 150 K and 300 K. We note that the PL integrated intensity increases sublinearly with the excitation intensity. The PL integrated intensity has been fitted by a sample power law I ∝ Lγ [13-15]; where I is the PL intensity, L is the excitation laser intensity and γ is a dimensionless exponent.

Fig. 3: Integrated photoluminescence intensity as function of excitation power of N related band in GaAsN(Si) and GaAsN QWs respectively (Fig.3.a) and (Fig.3.b).

For the undoped QW the slope are respectively 1.19, 1.64 and 1.41eV for T= 10, 150 and 300K and 0.97, 1.31 and 2.04 eV respectively for T= 10, 150 and 300K for Si-doped QW. We note that at low temperature T=10K the two samples have approximately the same slope γ =1 showing that the photoluminescence result from the bound exciton. But at high temperature for T=300 K, we note a strong difference for the slopes γ =1.41 for the undoped QW and γ = 2.04 for the Si-doped QW. This behavior can be explained by the fact that the carriers involved in the photoluminescence process are free type for Si-doped QW and free-and bound-exciton for undoped QW. The two studied samples Si-doped and undoped...
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Figures 4 shows PL spectra of GaAsN(Si) and GaAsN QWs for different temperatures. Figure 5 presents the temperature dependence of the PL peak energy of the two QWs. We note a strong “S-shape” behavior for the undoped QW asserting the strong density of nitrogen localized states. Slight that the transitions observed in the two quantum wells persists even at high temperature; therefore we can attribute to the GaAsN band state. In addition if we compare the two samples, we note that the undoped QW presents an “S-shape” at low temperature and its band gap energy is lower than the doped QW.

Then we can deduce that the incorporation of the silicon into the GaAsN QW reduces the defects and the coupling between the GaAsN band state and the nitrogen localised states. For the undoped QW, three temperature regions can be defined, labeled, I, II, III, and corresponding to a redshift, blueshift, and redshift behavior of the PL peak energy. In region I it is assumed that the exciton is bound to the localized states, in regions II to III region the exciton is progressing from a bound to a free state. The temperature dependence of the excitonic band gap is fitted using the Bose-Einstein expression [16] as shown in Fig. 4.

$$E_g(T) = E_g - a_g \left[ \frac{2}{\exp\left(\frac{E_g}{kT}\right) - 1} \right] + 1$$ \hspace{1cm} (1)

where $a_g$ (eV) represents the strength of the electron-phonon interaction and $T$ (K) is a temperature corresponding to the average optical phonon energy. For the case of the undoped QW, the PL intensity increases at 50K then it’s difficult to extract the thermal activation behavior by using the conventional Arrhenius formalism. To model the PL intensity we include the low temperature transport in GaAs barrier, by a coupled rate-equation approach.

$$I_{pl}(T) = Rn = \frac{G}{1 + \frac{q}{c} + \frac{q}{R} \beta}$$ \hspace{1cm} (2)

This model gives satisfactory description of the doped QW PL intensities in both low and high temperature regions, except for undoped QW at high power excitation. To describe the PL increase of undoped QW at intermediate temperature we must take in account between the increasing capture rate and the presence of a second channel thermal activation process which we can be attributed to carriers bounded to the nitrogen localized states. Therefore, Eq. (2) can be rewritten as [17].

$$I_{pl}(T) = Rn = \frac{G}{1 + \frac{q}{c} + \frac{q}{R} \left( \beta + \lambda \beta_i \right)}$$ \hspace{1cm} (3)

where $\beta_i \propto \exp\left( -\frac{E_{hi}}{K_BT} \right)$ describes the second carrier’s channel. $E_{hi}$ and $\frac{q}{c}$ and $\frac{q}{R}$ are the fitting parameters associated with the temperature dependence of the capture cross sections of the nitrogen localized states. A good fit using equation (3), demonstrated by the full curve in figure 5.

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3. Conclusion
In summary, we present photoluminescence measurements of Si-doped and undoped GaAs$_{1-x}$N$_x$ QWs growth on GaAs substrates by molecular beam epitaxy. We have noted that the introduction of the silicon in GaAs$_{1-x}$N$_x$ QWs affect considerably the nitrogen localized states density. At high power excitation the PL spectra maximum of Si-doped QWs blue-shifts from 1.45 to 1.48 eV. The "S-shape" form observed at low temperature in undoped QWs disappears for the Si-doped QWs. This effect shows that the incorporation of the silicon reduces the density of the bound localized states.

4. References