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Effect of rapid thermal annealing observed by photoluminescence measurement in $GaAs_{1-x}N_x$ layers

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Abstract

A set of $GaAs_{1-x}N_x$ samples with small nitrogen content were investigated by photoluminescence (PL) measurements as function of irradiance in order to investigate the effect of rapid thermal annealing (RTA) on photoluminescence (PL) properties. The analysis of PL spectra as function of irradiance and nitrogen content shows that the PL spectra associated to the $GaAs_{1-x}N_x$ layers are the result of the nitrogen localized state recombination. The results are examined as a consequence of a rapid thermal annealing (RTA). The variation of the emission band peak energy (E_p), at 10 K as a function of irradiance, is fitted by a theoretical model taking into account two types of nitrogen localized states. The variation of the PL intensity versus irradiance in the range from 1.59 to 159 W/cm^2 for different $GaAs_{1-x}N_x$ samples confirm that the PL spectra result from the nitrogen localized state recombination.

Keywords: GaAsN; Molecular beam epitaxy; Rapid thermal annealing (RTA); Photoluminescence (PL); Irradiance; Slope

1. Introduction

Narrow band gap nitrides such as GaAsN and GaInNAs are being studied intensively for both their fundamental properties [1–6] and their potential for long wavelength opto-electronic device applications on GaAs substrates [7–9]. What derives such interest is that nitrogen incorporation of only a few percents in GaAs or GaInAs induces an unusual decrease in the band gap energy of synthesized alloys. Recently, this anomalous effect has been successfully used to develop 1.3 μm vertical cavity surface-emitting lasers pseudomorphically grown on GaAs substrates [8,9], making the GaInNAs material a very promising candidate for datacom applications.

However, for both GaAsN and GaInAsN materials, the higher the nitrogen incorporation, the weaker the alloy luminescence efficiency. Rapid thermal annealing (RTA) is usually performed on these ternary and quaternary alloys to remove non-radiative defects [10–12] from ion damage, impurities coming from the plasma source, and non-radiative recombination fundamental to the band structure are some of the accepted reasons to explain the decreasing efficiency of the radiative recombination even in the case when N content is less than 1–2%. Moreover, the growth temperature of N-containing structures has to be much lower than that for the N-free samples to suppress phase separation effects. The low-temperature growth is also one of the reasons for lower photoluminescence (PL) intensity. Post-growth annealing as a rapid thermal annealing has been found to improve the PL intensity to a reduction of N-related defects [13–21]. Wang et al. [22] demonstrate highly efficient radiative recombination in GaAsN layers by optimizing the radio-frequency (RF) plasma nitrogen source operation, growth regimes and post-growth annealing. Nonetheless, an undesirable effect is often induced by RTA: the emission peak shifts toward the blue as rapid thermal annealing proceeds, which prevents long wavelengths with acceptable intensities to be reached. Understanding the origin of such a blue-shift should help in having a better insight into the as-grown material as well as in to reach a given emission wavelength [23].

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In this paper, we present optical studies of as-grown and (RTA) $GaAs_{1-x}N_x$ layers with $x = 0.5$ and 1.5% using PL measurements as function of the irradiance. The PL spectra analyse as function of nitrogen content, irradiance and rapid thermal annealing treatment were studied in detail.

2. Experimental details

The GaAsN samples were grown on (0 0 1) GaAs substrates by molecular beam epitaxy (MBE) equipped with a radio-frequency (RF) plasma as the nitrogen radical source to decompose N_2 into N active species. The N_2 flux is controlled by a mass flow regulator.

The samples consist of a GaAs buffer layer and a 0.1–0.2 μm $GaAs_{1-x}N_x$ grown at 450 °C. Lower growth temperatures lead to higher nitrogen incorporation but increased growth temperature results in better optical properties [24–26]. N_2 rates ranged between 0.2 and 0.6 sccm, and RF power from 250 to 450 W. Rapid thermal annealing (RTA) was performed for 90 s under N_2 flow ambient at 680 °C. During RTA, the samples were put on GaAs wafer face to face to prevent loss of arsenic at high temperatures. The crystal quality and the nitrogen content of the samples were determined from the high-resolution X-ray diffraction (HRXRD) measurements and varied from 0.5 to 1.5%. Optical measurements were carried out at temperature ranging from 10 to 300 K in a variable temperature closed-cycle helium cryostat using a solid state diode-pumped, frequency-doubled Nd:vanadate (Nd:YO_4) laser with the 532 nm line and detected through a Jobin–Yvon monochromator by an avalanche Si detector associated with a sensitive lock-in amplification system. The irradiance was in the range from 1.59 to 159 W/cm^2.

3. Results and discussion

Fig. 1(a) shows the PL spectra of as-grown and annealed $GaAs_{1-x}N_x$ samples at 680 °C for 90 s with nitrogen content of 0.5%. The spectra of as-grown sample is, respectively, governed by GaAs line at 1.513 eV, carbon impurity at 1.492 eV and three bands situated, respectively, at 1.336, 1.362 and 1.390 eV. For the (RTA) sample, the intensity of the band situated at 1.390 eV increases and becomes more clearly resolved. We have attributed the 1.390 eV to the $GaAs_{1-x}N_x$ band gap energy and the 1.336 and the 1.362 eV to the nitrogen localized states [2,24]. In addition, we note a small improvement of the PL efficiency at about 20% after the (RTA) treatment. We can conclude that the (RTA) treatments improve the PL quality of this sample with no material transformation or phase separation [27].

For $GaAs_{1-x}N_x$ samples with $x = 1.5\%$, we have plotted in Fig. 1(b) the PL spectra before and after rapid thermal annealing at 680 °C for 90 s. For the two spectra, we show systematically the two known GaAs related near-band-edge

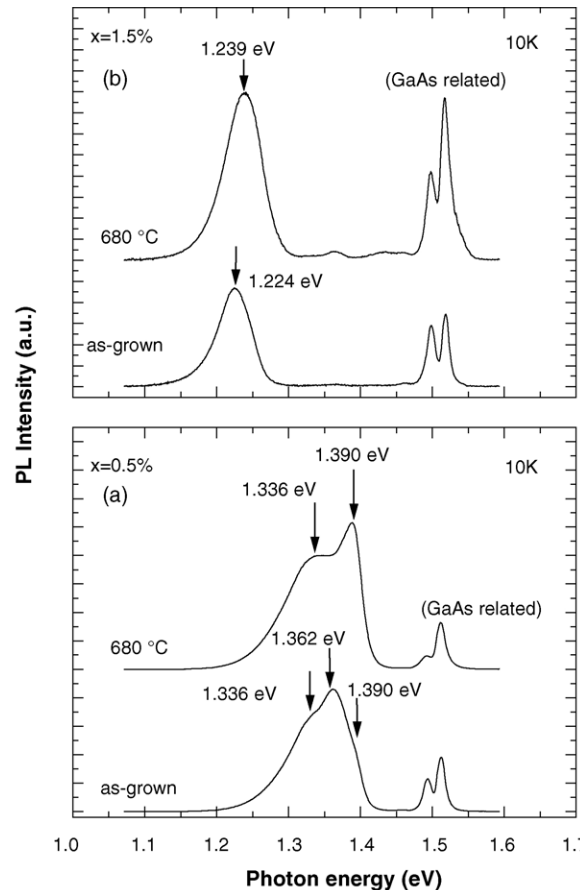

Fig. 1. Ten kelvin of PL spectra depicting the influence of RTA treatment on $GaAs_{0.995}N_{0.005}$ and $GaAs_{0.985}N_{0.015}$ layers for as-grown and annealed samples at 680 °C for 90 s.

emissions together and broad peaks situated, respectively, at 1.224 and 1.239 eV for as-grown and annealed samples, attributed to the band gap energy of $GaAs_{1-x}N_x$ layers. As seen in Fig. 1(b), we note that the annealed treatment, for 90 s at 680 °C, produces a considerable improvement in the photoluminescence intensity by factors of ∼2 and blue-shifted the PL maximum position corresponding to the $GaAs_{1-x}N_x$ band-gap energy by 15 meV. This blue-shift can be interpreted by a local decrease of the nitrogen content in the sample.

For understanding the nature of the photoluminescence of these samples, irradiance dependence of the PL spectra is an important consideration. In Fig. 2(a) and (b) and Fig. 3(a) and (b), we present the irradiance dependence of the PL spectra of $GaAs_{1-x}N_x$ layers with ($x = 0.5\%$) and ($x = 1.5\%$), before and after a 680 °C for 90 s rapid thermal annealing (RTA) at $T = 10$ K. The analysis of $GaAs_{1-x}N_x$ ($x = 0.5\%$) spectra shows that at low irradiance, PL spectra are essentially formed by localized states. At high enough irradiance nitrogen localized states become saturated and the peak corresponding to $GaAs_{1-x}N_x$ band gap energy appears slightly.

For $GaAs_{1-x}N_x$ ($x = 1.5\%$) samples, as seen in Fig. 3(a) and (b), we note that the intensity ratio between $GaAs_{1-x}N_x$