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Photoluminescence in n and p modulation-doped GaInNAs/GaAs quantum wells

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ABSTRACT

Experimental results concerning the steady-state photoluminescence (PL) studies in n and p modulation doped and undoped GaInNAs/GaAs quantum wells are presented. The effects of modulation, type of doping and nitrogen concentration on the PL and the temperature dependence of the band gap, carrier localization and non-radiative recombination are investigated. Increasing the nitrogen composition decreases energy band gap as expected. The n-type modulation doping eliminates most of the defect-related effects and blue shifts the energy band gap. However, the p-type doping gives rise to additional features in the PL spectra and red shifts energy band gap further compared to the n-type-doped material.

1. Introduction

GaInNAs alloys have been attracting a great deal of attention recently because of their potential applications in long wavelength optoelectronic devices for optical communications. They have considerable advantages to over conventional narrow band gap materials due to lattice match to GaAs substrate, large conduction band offset in GaInNas/GaAs quantum wells (QWs) and suitability to make vertical cavity devices with good refractive index contrast GaAs/GaAlAs DBRs. The addition of small amount of nitrogen reduces the band gap to allow an extensive control of band gap energy. But it degrades the material quality due to small atomic radius and high electro negativity of N atoms. The material quality can be improved in a limited range using some techniques like in situ [1] or post-growth annealing [2] and Sb adding as surfactant during the growth [3]. Photoluminescence (PL) spectra of undoped GaInNAs/GaAs QWs are usually dominated by localized exciton emissions related to N complexes [4]. In this work, we eliminate fully or reduce the transitions associated with exciton localization by modulation doping the QWs as to raise the Fermi level and investigate the influence of high carrier density on the PL emission from GaInNAs/GaAs QWs.

2. Experimental details

One undoped sample containing an InGaAs/GaAs and one GaInNAs/GaAs single QWs, and four modulation-doped samples are investigated in this work (Table 1). Modulation-doped samples consists of three 7 nm GaInNAs QWs, separated by GaAs barriers with a 20 nm doped (for n-type Si and for p-type Be) and a 5 nm undoped spacer layer as shown in Fig. 1. Steady-state PL measurements were carried out using 532 nm line of Nd-YAG laser as excitation source and a cooled InGaAs detector coupled with a 1/3 m high-resolution monochromator for dispersion and detection at temperatures between $T = 10$ and 300 K.

3. Results and discussion

Fig. 2 shows the PL spectra from undoped, n and p modulation-doped samples at $T = 10$ K. For the undoped sample the two peaks in the spectra correspond to the InGaAs and GaInNAs QWs. The emission intensity of InGaAs QW is plotted 20 times smaller than the original value. If we compare with InGaAs QW emission, the PL peak of undoped GaInNAs QW is 285 meV red-shifted, broadened and its intensity decreased (by a factor of 20) as a result of 1% N incorporation. The n-type modulation doping blue shifts the radiation peak energy compared to the undoped QW because of Moss-Burstein shift [5] associated with the presence of high electron density, $n_{2D} = 4.0 \times 10^{12}\,\mathrm{cm}^{-2}$ which is clear from the PL spectra of undoped and modulation-doped QW samples with

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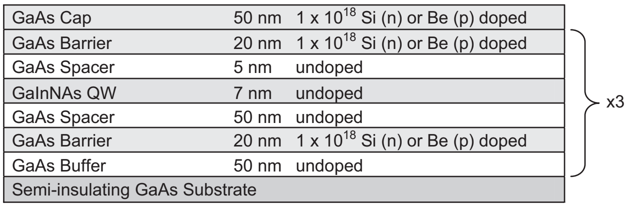
Table 1
Growth parameters of the samples investigated in this work

Sample I.D.	Structure	Well width (nm)	Indium (%)	Nitrogen (%)	Growth	Sample source
1471	SQW InGaAs	11	20	0	MBE	LAAS
	SQW GaInNAs	7	33	1		
HN004	n-Modulation-doped 3QWs	7	30	0.4	MOVPE	Helsinki
HN01	n-Modulation-doped 3QWs	7	30	1	MOVPE	Helsinki
1930	n-Modulation-doped 3QWs	7	30	1.5	MBE	LAAS
1931	p-Modulation-doped 3QWs	7	30	1.5	MBE	LAAS



GaAs Cap	50 nm	1 x 10^{18} Si (n) or Be (p) doped
GaAs Barrier	20 nm	1 x 10^{18} Si (n) or Be (p) doped
GaAs Spacer	5 nm	undoped
GaInNAs QW	7 nm	undoped
GaAs Spacer	50 nm	undoped
GaAs Barrier	20 nm	1 x 10^{18} Si (n) or Be (p) doped
GaAs Buffer	50 nm	undoped
Semi-insulating GaAs Substrate		

Fig. 1. Layer structure of the modulation-doped samples.

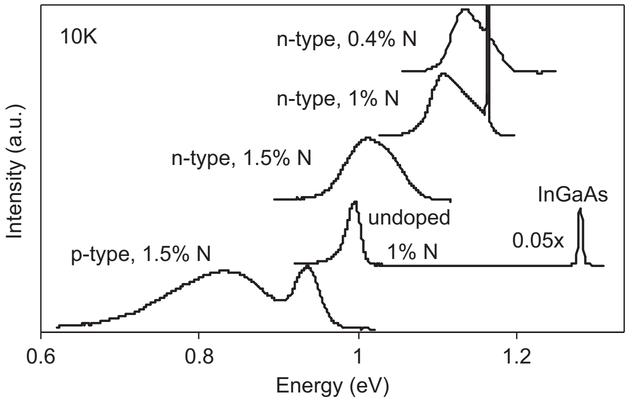


Fig. 2. PL spectra of the undoped and modulation-doped samples at 10 K. The emission intensity of InGaAs QW is plotted 20 times smaller.

same nitrogen concentration (1%). The p-type modulation doping causes a red shift compared to the n-doped sample with the same nitrogen content (1.5%). It is also evident from Fig. 2 that increasing the nitrogen concentration decreases the band gap of modulation-doped samples as commonly reported for undoped GaInNAs alloys [6].

Fig. 3 shows spectral emission peaks of undoped, n- and p-type modulation-doped samples. The shape of PL emission from the InGaAs QW is Gaussian-like and symmetrical as shown in Fig. 3(a). The emission from undoped GaInNAs QW has, however, an asymmetric shape with a low energy exponential tail indicating the presence of localized states [6]. The low energy tail disappears almost completely from the PL in n-type modulation-doped sample as shown in Fig. 3(c). We believe that the reason for the lack of localized state associated recombination is because these states below the conduction band are completely filled up by excess electrons due to modulation doping. Therefore, the PL radiation is simply due to the band-to-band transition. The PL spectra in the p-type modulation-doped sample shown in Fig. 3(d) consist of two clear peaks. The higher energy peak is due to transitions of photo-excited electrons from the lower-lying localized states below the conduction to valance band where the holes have a broad momentum distribution [7]. The broad spectrum at lower energy is only observed, however, in Be-doped p-type samples. Such broad emissions are usually reported in samples containing a very high density of defects and may therefore be associated with the high nitrogen content [8]. However, the samples coded 1930 and 1931 have identical growth conditions, the only difference being the type of modulation doping. We believe therefore, that the Be dopant in the p-type sample may be responsible for the defect-related broad emission peaking at 0.82 eV. Fig. 4 shows the temperature dependence of peak emission energies of the undoped and modulation-doped samples. The well-known S-shaped temperature dependence of peak emission energy of undoped GaInNAs sample is also shown in Fig. 4(b) [6]. In the modulation-doped samples the S-shaped behavior is completely missing because the recombination is dominated by band-to-band transition rather than localized exciton transition at low temperature as shown in Fig. 4(a) [8]. In fact, the peak emission energy in all modulation-doped samples is almost temperature independent at low temperature range ($T<80$ K), which can be understood using BAC model. At low temperatures, the conduction band edge is more close to localized nitrogen energy level. Hence, it would be more localized in nature, which has weak temperature sensitivity. However, at higher temperatures, more of higher laying band states cross over the nitrogen level, and conduction band is much more extended like in nature, leading to more band-like temperature dependence. The temperature gradient (dE/dT) of peak emission energy in the linear region ($T>250$ K) has been calculated for all the samples and are tabulated in Table 2, and the PL peak at room temperature of all the samples are also tabulated. The trend towards decreasing temperature dependence (dE/dT) with increasing N content is very clear from the table. The activation energies of dominant non-radiative recombination mechanism can be obtained from the temperature-dependent PL intensities [6]. A typical example Arrhenius plot of the peak PL intensity ($\ln[(I_0/I)-1]$ versus $1/T$ is shown in Fig. 5. The activation energies obtained for all the samples are tabulated in Table 3.

The excitation power dependence of peak emission energy of undoped and modulation-doped samples containing identical nitrogen is shown in Fig. 6. For the undoped sample the peak emission energy shifts rapidly to higher energies with increasing excitation intensity then saturates at a higher excitation powers. In case of n-type modulation-doped sample the peak emission energy is independent of the excitation power.

In the undoped sample increasing the pump power produces higher density of free carriers in the conduction and valance bands producing a high density of excitons that fill up the localized states. This leads to domination of free carrier recombination to overall radiation of undoped GaInNAs QWs under high excitation giving rise to the observed blue shift. In the n-modulation-doped samples, the presence of high density of electrons has already filled up the localized states. Therefore, any excess electrons excited to conduction band by optical