High temperature photoluminescence efficiency and thermal stability of (InGa)(AsN)/GaAs quantum wells

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The temperature dependence of the photoluminescence (PL) efficiency of (InGa)(AsN)/GaAs single quantum wells (QWs) has been studied from 10 to 500 K. The PL intensity of N-containing samples is almost constant from room temperature to 500 K, in contrast to what is observed in (InGa)As QWs grown under the same conditions. This thermal stability increases for an increase in nitrogen content. We discuss these effects in terms of strain compensation at high nitrogen concentrations. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1409333]

In recent years, N-containing arsenides such as (InGa)(AsN) have attracted considerable attention both for their fundamental properties and for their promising optoelectronic applications.[1–5] The incorporation of small amounts of nitrogen leads to dramatic changes in the electronic properties of the (InGa)As host lattice. The most striking effects are a strong band gap reduction (about 100 meV per N percent)[1,2] and a large increase in the electron effective mass.[6] The large band gap redshift has been successfully exploited in the realization of highly efficient multijunction solar cells[7] and lasers emitting in the wavelength range of interest for optical fiber communications (i.e., at 1.3 and 1.55 μm).[4,5,8–10] Furthermore, because of strong carrier confinement, a characteristic temperature higher than that found in conventional (InGa)(AsP)/InP lasers is expected for the (InGa)(AsN)/GaAs system.[4,5]

Although a great deal of effort has been made to obtain high quality materials, data reported in the literature show that the photoluminescence (PL) efficiency in (InGa)(AsN) alloys is lower than that found in N-free material.[1,11–15] Moreover, the crystal quality deteriorates for increasing N concentration. This can be attributed to the large miscibility gap between GaAs and GaN, to the presence of defects,[1] and to composition nonuniformity.[14] At the same time, nitrogen addition to (InGa)As alloys is predicted to decrease the total amount of strain,[1] as also inferred by x-ray absorption fine-structure techniques.[16] In some cases, postgrowth annealing leads to improvement of the optical properties.[11,17]

In this letter, we compare the temperature dependence of the PL efficiency of several (InGa)As and (InGa)(AsN) single quantum wells (QWs) measured in the temperature range of 10–500 K. The following effects were observed. (i) All samples investigated exhibit intense PL emission well above room temperature (RT). (ii) In contrast with previous reports, the PL peak intensity as well as the integrated PL intensity of N-containing samples is comparable to those of corresponding N-free QWs in the low temperature range ($10\,\mathrm{K}<T<270\,\mathrm{K}$), and is stronger in the high temperature range ($270\,\mathrm{K}<T<500\,\mathrm{K}$). (iii) High thermal stability is observed for the PL efficiency of (InGa)(AsN) QWs above 270 K, while no such behavior is seen in (InGa)As reference samples. These findings are discussed in terms of improved quality of the lattice due to a strain compensation effect induced by N.

Several (InGa)(AsN)/GaAs heterostructures were grown by solid source molecular beam epitaxy. N_2 cracking was obtained by using a radio frequency plasma source. The structure of the samples consists of a 500 nm thick GaAs buffer layer, an (InGa)(AsN) QW, and a 100 nm thick cap layer. A reference sample without nitrogen was grown for each subset of samples having the same indium content and well width but with differing nitrogen concentrations, y. The properties of the samples are listed in Table I. The nitrogen concentration was determined by a combined analysis of x-ray diffraction and optical data. No postgrowth annealing was performed. The PL was excited by the 515 nm line of an Ar^+ laser and the signal was spectrally analyzed by a single 1 m monochromator and collected by a Ge detector cooled at 77 K.

The PL spectra of an (InGa)(AsN) QW and of the corresponding N-free reference QW are plotted in Fig. 1 for

TABLE I. List of the $In_xGa_{1-x}As_{1-y}N_y$/GaAs single quantum wells investigated. x is the indium content, y is the nitrogen content, and L is the quantum well thickness. The photoluminescence peak energy, $h\upsilon_P$, at room temperature is also given.

Sample	x	y	L (nm)	$h\upsilon_P$ (eV) at RT
mm340	0.34	0	7.0	1.06
mm369	0.34	0.007	7.0	1.01
mm344	0.41	0	7.0	1.01
mm362	0.41	0.022	7.0	0.87
mm361	0.41	0.031	7.0	0.83
mm378	0.38	0	8.0	1.07
mm383	0.38	0.052	8.2	0.79

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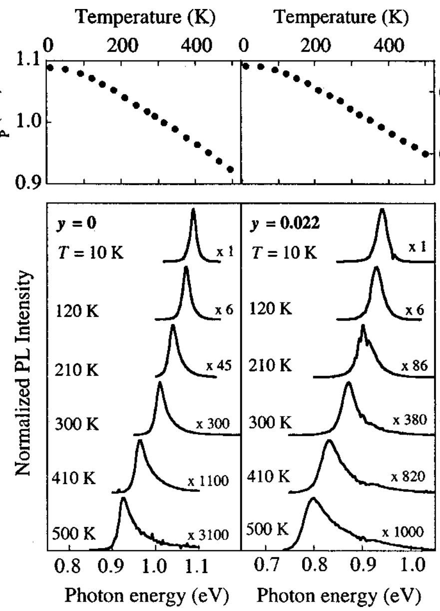

FIG. 1. Normalized PL spectra recorded at different temperatures (bottom) and PL peak energy dependence on the temperature (top) of an $In_{0.41}Ga_{0.59}As$/GaAs QW (left) and of an $In_{0.41}Ga_{0.59}As_{0.98}N_{0.02}$/GaAs QW (right). Normalization factors are given for each spectrum. Laser power density $P = 60$ W/cm^2.

temperatures ranging from 10 to 500 K, where a strong PL signal is still observed. For $T < 100$ K, the PL line shape is slightly asymmetric on the low energy side, this feature being more evident for low laser excitation intensities.[18] The low-energy tail is due to emission from localized states induced by alloy fluctuations, discussed extensively in previous work.[18] A signature of the dominant role of localized states in near band-gap emission processes is provided by an S-shaped temperature dependence of the PL peak energy, $h\nu_P$.[18,19] Since this feature is absent here, as can be seen in the upper part of Fig. 1, we assume that localized states are saturated at the high excitation intensities used in this work. Above 200 K, the PL spectra show an exponential high-energy tail due to emission from thermally populated delocalized states of the well, and $h\nu_P$ decreases almost linearly with T. The rate of this decrease is considerably smaller in the N-containing sample, in agreement with previous results.[18] In fact, the incorporation of N into (InGa)As QWs leads to a reduced thermal redshift, whose slope above RT ($\sim$0.36 meV/K for the $y = 0.022$ sample shown in Fig. 1) is below the 0.40 meV/K limit required for laser devices.[10]

The temperature dependence of the PL integrated intensity, $I_{PL}(T)$, is shown in Fig. 2 for three sets of QWs having the same indium concentrations and well widths but differing in their nitrogen content. A similar temperature dependence was found for the PL peak intensity (not shown here). In (InGa)As samples (open circles), I_{PL} does not clearly depend on the indium concentration. Moreover, I_{PL} decreases by more than three orders of magnitude upon going from $T = 10$ to 500 K. In (InGa)(AsN) QWs, $I_{PL}(T)$ shows quite different behavior, which strongly depends on the N content. The thermal quenching of I_{PL} for the sample with the lowest amount of nitrogen ($y = 0.007$) is very similar to that of its N-free reference over the whole temperature range, while the absolute value of I_{PL} is stronger by a factor of about 10. In QWs with high nitrogen content ($y = 0.022$, 0.031, and 0.052), I_{PL} is approximately equal to or slightly lower than that of the corresponding N-free sample for $T < 270$ K, while it is much higher at high T.

In order to give a quantitative estimate of the PL thermal stability, we introduce the ratio, $\eta(T)$, of $I_{PL}(T)$ measured in (InGa)(AsN) QWs to that measured in the corresponding (InGa)As sample, both normalized at their value for $T = 10$ K. Therefore, $\eta(T = 500\text{ K})$ suitably measures the thermal stability of our samples at high T. We find that this thermal stability improves nearly exponentially with the nitrogen content, as shown in Fig. 3 on a semilogarithmic scale.

It is worth noting that all samples show a rapid decrease in PL efficiency, which starts at very low T. This cannot be accounted for by a thermal escape mechanism of one or both carriers from the QW to the GaAs barrier states, because of the high confinement energy of carriers in our QWs. Recently, the thermal quenching of the PL intensity at low T in a (InGa)(AsN) QW has been related to emission from strongly localized states, in analogy with amorphous

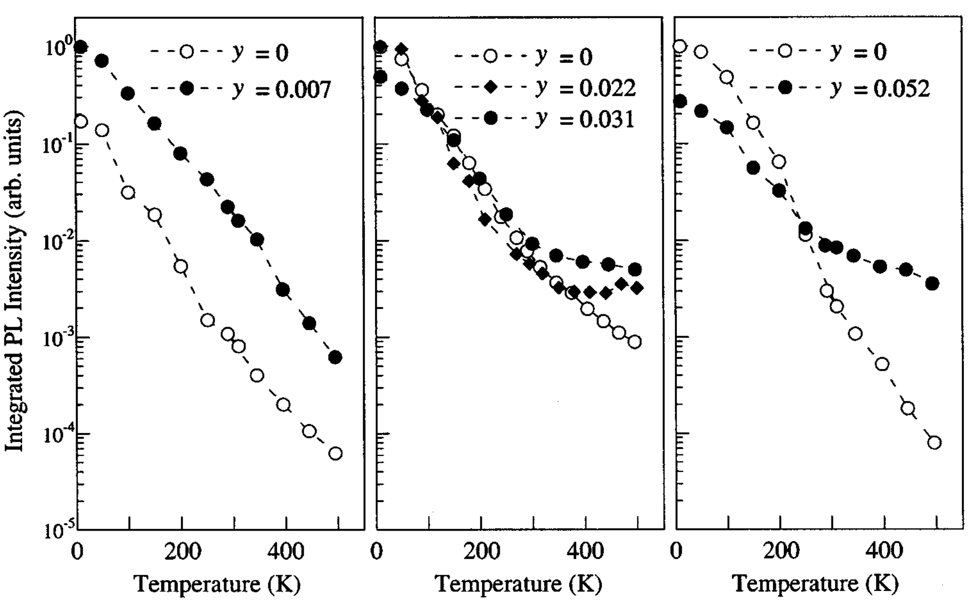

FIG. 2. Temperature dependence of the integrated photoluminescence intensity of three subsets of $In_xGa_{1-x}As_{1-y}N_y$/GaAs QWs for differing nitrogen contents, y. The integrated photoluminescence intensity was normalized to the most intense sample for each subset of samples considered. The indium content, from left to right, is $x = 0.34$, 0.41, and 0.38. Dashed lines are guides to the eye. Laser power density $P = 60$ W/cm^2.

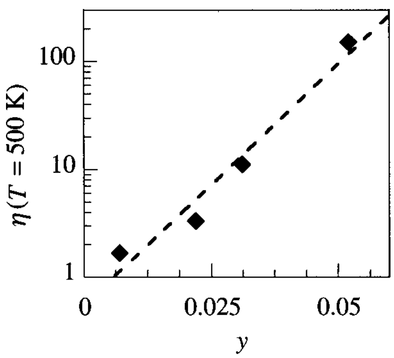

FIG. 3. $\eta(T=500\ \mathrm{K})$, an estimate of the PL thermal stability, as a function of the nitrogen content y. The dashed line is a guide to the eye.

semiconductors.[19] However, carrier localization effects can be neglected in the present PL spectra even in the limit of low T, as previously discussed. A simple kinetic model[20,21] applied to N-containing samples indicates that the carrier activation energy is of order of a few tens of meV. This suggests that the energy levels of nonradiative recombination channels should be close to the ground state of the well. As far as the origin of these defects is concerned, we point out that our (InGa)As QWs are highly strained, because of the high indium concentration and large well width, which are both needed to reach long emission wavelengths. The resulting strain may lead to the formation of defects such as dislocations and, under suitable growth conditions, to a two-dimensional to three-dimensional transition, as seen in transmission electron microscopy measurements.[15] On the other hand, the incorporation of nitrogen leads to partial compensation of the net compressive strain[16] and results in a low density of dislocations in the material, that is, in a low number of nonradiative channels. As T is increased, these channels are progressively saturated by thermally activated carriers and I_{PL} reaches an almost constant value, which depends on the total number of nonradiative recombination centers. This could account for the enhancement of the PL thermal stability for increasing nitrogen content reported here.

In conclusion, we studied the PL efficiency of high-quality (InGa)(AsN)/GaAs single quantum wells in a wide temperature range, from 10 to 500 K. (InGa)(AsN) QWs show high thermal stability of the PL intensity from RT up to 500 K. We attribute this effect to a strain compensation effect due to nitrogen incorporation into highly strained (InGa)As QWs. We believe that the thermal properties of (InGa)(AsN) discussed here are very promising for the development of optoelectronic devices operating at and above RT.

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