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Wavelength extension of GaInAs/GaIn(N)As quantum dot structures grown on GaAs

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Abstract

Self-assembled GaInAs quantum dots (QDs) embedded in GaIn(N)As were grown by atmospheric pressure metalorganic vapor phase epitaxy. The dependence of the photoluminescence (PL) properties on the material composition of the barrier layer was investigated. The emission wavelength and intensity of the QDs could be tuned by controlling the indium and nitrogen compositions in the barrier layer. By using a $Ga_{0.8}In_{0.2}As$ barrier layer, the room-temperature PL wavelength of the QDs was extended up to 1.42 μm and the PL intensity was increased by a factor of three compared to the conventional GaInAs/GaAs QD structure. Preliminary results show that by using N-containing $Ga_{0.85}In_{0.15}NAs$ as a barrier layer instead of $Ga_{0.85}In_{0.15}As$ an increase in the PL wavelength and intensity in the 1.3 μm wavelength range can be obtained.

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Keywords: A1. Photoluminescence; A3. Metalorganic vapor phase epitaxy; B2. Semiconducting materials

1. Introduction

In the last few years considerable attention has been devoted to material and device research for 1.3 μm laser structures grown on GaAs substrates. Two methods to realize 1.3 μm light emission have been demonstrated. One approach is to use self-assembled InAs or GaInAs quantum dots (QDs) in the active region [1–3]. The transition energy of the QDs can be lowered and tuned by embedding the islands in an GaInAs quantum well, which leads to lower quantum confinement and reduced strain in the QDs [4–7]. The other method is to use GaInNAs quantum wells [8–10] or QDs [11,12]. Due to the large band gap bowing, adding a few percent of nitrogen into GaInAs is sufficient to enable fabrication of long-wavelength active materials on GaAs. However, we have observed that the growth of GaInNAs QDs by metalorganic vapor phase epitaxy (MOVPE) is problematic since the incorporation of nitrogen is hindered by the large indium composition required to form the QDs [12]. Therefore, it could be more beneficial to use GaInAs as the QD material and bury them in GaInNAs. In the present study, we have grown GaInAs/GaIn(N)As QD structures by MOVPE and investigated the effect of the composition of the barrier layer on the photoluminescence (PL) properties of the structures.

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2. Experimental procedure

The samples were grown on semi-insulating GaAs (1 0 0) substrates in a horizontal MOVPE reactor at atmospheric pressure. Hydrogen was used as a carrier gas. Trimethylgallium (TMGa), trimethylindium (TMIn), tertiarybutylarsine (TBAs) and dimethylhydrazine (DMHy) were used as sources for gallium, indium, arsenic and nitrogen, respectively. In the growth procedure a 100 nm thick GaAs buffer layer was first grown at 650°C. Then, 5 ML of $Ga_{0.5}In_{0.5}As$ was deposited at 550°C with a growth rate of 2 ML/s. After a growth interruption of 10 s with TBAs supply, the islands were covered at 550°C using three different methods. In the first method a conventional GaAs cover was used, while in the second the islands were first buried in a 10 nm thick $Ga_{1-x}In_xAs$ ($0.1 \leqslant x \leqslant 0.25$) layer and then capped by a 50 nm of GaAs. The third method was similar to the second one, but the overgrowth was done with a 10 nm thick $Ga_{0.85}In_{0.15}NAs$ layer using different DMHy/TBAs ratios. The QD compositions mentioned here are gas phase compositions. A schematic illustration of the sample structure is shown in Fig. 1.

The areal density of the islands was determined by atomic force microscopy (AFM) to be $2.4 \times 10^{10}\,cm^{-2}$. Since the growth conditions of the islands were not completely optimized, two types of small islands having an average height of 5 and 8 nm were observed. The optical properties of the samples were investigated by photoluminescence (PL) measurements performed at 10 K and at room temperature. The 488 nm line of an argon ion laser was used for excitation. The luminescence was dispersed with a 0.5 m monochromator and detected by a liquid-nitrogen-cooled germanium detector.

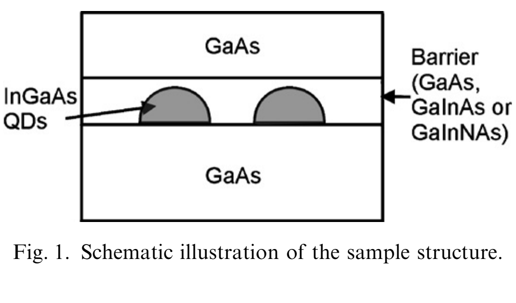

Fig. 1. Schematic illustration of the sample structure.

3. Results and discussion

The use of GaInAs as a barrier layer was studied first and compared to the conventional GaAs coverage. Figs. 2(a) and (b) show the dependence of the room-temperature PL wavelength and the PL intensity of the QDs on the indium composition of the GaInAs barrier. As expected, the emission wavelength redshifts from 1.27 to 1.42 μm when the In composition of the barrier is increased from 0% to 25%. Since the lattice constant of the GaInAs barrier increases as the In composition is increased, the strain in the QDs is partly reduced due to relaxation of lattice constraint in the growth direction. This together with the decrease of the in-plane potential barrier height leads to the increase in the PL wavelength. The PL intensity increases by a factor of three up to the In composition of 15%. Further increase in the InAs mole fraction results in larger total strain and therefore leads to dislocation formation and degradation of the PL intensity. To investigate whether the PL intensity of the longest wavelength samples could be improved, samples with the

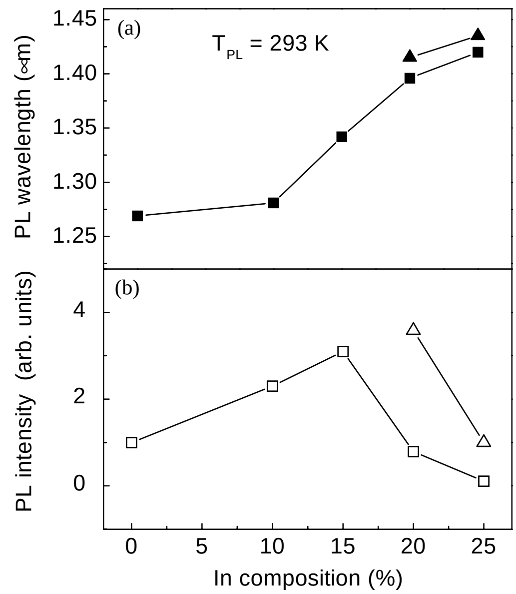

Fig. 2. (a) Room-temperature PL wavelength and (b) intensity for QDs embedded in 10 nm of GaInAs as a function of the In composition of the barrier layer. The triangles show the respective data for the barrier layer thickness of 5 nm.

barrier thickness of 5 nm were grown. This resulted in considerable increase in the PL intensity of the sample having 20% indium in the barrier. The emission wavelength redshifted slightly when the barrier thickness was reduced, which could be due to run-to-run differences. The results presented above indicate that by embedding the GaInAs QDs in GaInAs instead of GaAs, the emission wavelength can be increased and the PL intensity can be improved.

The GaInAs QDs were next covered by a 10 nm thick $Ga_{0.85}In_{0.15}NAs$ layer. The N composition was increased by increasing the DMHy/TBAs ratio. Fig. 3 shows the PL spectra measured at 10 K. The QDs in samples (a) and (b) are covered with GaAs and $Ga_{0.85}In_{0.15}As$, respectively. The barrier layer in samples (c)–(f) is $Ga_{0.85}In_{0.15}NAs$ grown with DMHy/TBAs ratios of 13.3, 19, 24, and 32.3, respectively. Based on previous results [13], the N composition of the barrier is estimated to vary between 0.5% and 3.5%. Spectra (a)–(c) exhibit two transition peaks. Since the relative intensity of these two peaks does not change with excitation power we attribute the higher energy line to a second distribution of QDs with smaller sizes. As the embedding material is changed from GaAs to $Ga_{0.85}In_{0.15}As$, the PL peaks redshift and the intensity increases. As nitrogen is introduced into the barrier with DMHy/TBAs ratio of 13.3

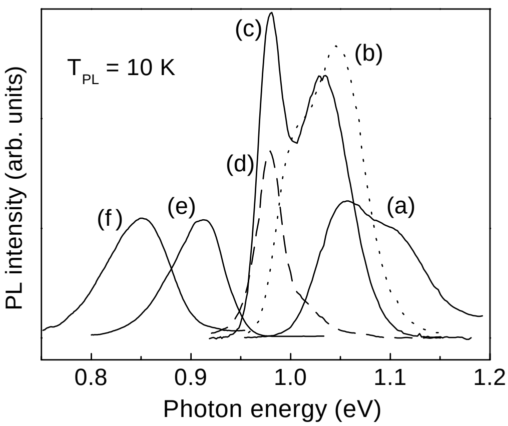

Fig. 3. Low-temperature PL spectra of QD samples embedded in (a) GaAs, (b) $Ga_{0.85}In_{0.15}As$, and (c)–(f) $Ga_{0.85}In_{0.15}NAs$ grown with DMHy/TBAs ratios of 13.3, 19, 24, and 32.3, respectively. The PL spectra (e) and (f) have been multiplied by a factor of 4 and 60, respectively.

the PL peaks redshift further and the intensity of the lower energy peak increases with respect to the higher energy peak. Since the lattice constant of $Ga_{0.85}In_{0.15}NAs$ is smaller than that of $Ga_{0.85}In_{0.15}As$ the energy shift between samples (b) and (c) can not be due to strain reduction effect. We have observed a redshift of the PL peak when DMHy flush is used instead of TBAs during the 10 s growth interruption after the growth of the QDs. Although the QDs in this work were flushed with TBAs, N may still modify the QDs during the growth of the GaInNAs barrier. This together with the decrease in the conduction band barrier height due to the bandgap shrinkage of GaInNAs explains the redshift of the PL peaks.

When the conduction band discontinuity decreases close enough to the energy states of the smaller QDs, the PL intensity of these QDs decreases with respect to larger QDs. When the DMHy/TBAs ratio is increased to 19 (sample (d)), the conduction band edge of the barrier comes further down in energy and pulls the electron states of the smaller QDs closer to that of the larger ones. The intensity of the higher energy PL peak decreases since the wavefunction spreads and penetrates into the barrier layer. Although the N composition of the barrier layer increases between samples (c) and (d), this is not sufficient enough to shift the PL peak of the larger QDs. Further increase in the DMHy/TBAs ratio results in type II band alignment when the conduction band edge of the barrier material drops below that of strained $Ga_{0.5}In_{0.5}As$ QDs. The PL peak redshifts, the intensity drops drastically, and the linewidth of the PL peak increases when the recombination occurs between electrons in the barrier material and holes in $Ga_{0.5}In_{0.5}As$ QDs (samples (e) and (f)).

Fig. 4 shows the development of the PL wavelength and intensity of the larger QDs as a function of the DMHy/TBAs ratio. When the DMHy/TBAs ratio is increased from 0 to 13.3, the PL wavelength of the $Ga_{0.85}In_{0.15}NAs$ covered QDs redshifts by 40 nm and the PL intensity increases a little. The PL intensity stays higher than that of the sample covered only with GaAs until the DMHy/TBAs ratio is increased over 20. Although the PL wavelength of the sample grown with the DMHy/TBAs ratio of 32.3 is 1.46 μm, the

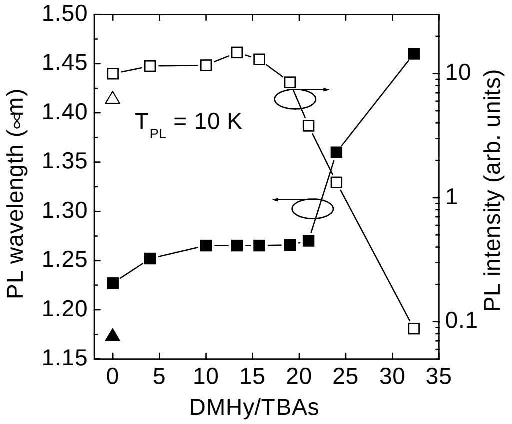

Fig. 4. Dependence of the PL wavelength and intensity of the QDs on the DMHy/TBAs ratio used in the growth of the barrier layer. The triangles show the respective data for QDs embedded in GaAs.

PL intensity is two decades smaller compared to the sample covered with $Ga_{0.85}In_{0.15}As$. Temperature dependent PL measurements of these samples indicate an increasingly rapid decay of the PL intensity with increasing N composition and no room-temperature luminescence was detected from samples grown with DMHy/TBAs ratios larger than 21.

4. Conclusions

GaInAs/GaIn(N)As QD structures were fabricated by atmospheric pressure MOVPE. The dependence of the PL properties on the composition of the barrier layer was investigated. By embedding the $Ga_{0.5}In_{0.5}As$ QDs in a 5 nm thick $Ga_{0.8}In_{0.2}As$ layer the room-temperature PL wavelength was extended up to 1.42 μm and the PL intensity was increased by a factor of three compared to the conventional GaAs cover. By using N-containing $Ga_{0.85}In_{0.15}NAs$ as a barrier layer instead of $Ga_{0.85}In_{0.15}As$ an increase in the PL wavelength and intensity in the 1.3 μm wavelength range was observed.

References

[1] G. Park, O.B. Shchekin, S. Csutak, D.L. Huffaker, D.G. Deppe, Appl. Phys. Lett. 75 (1999) 3267.
[2] D.L. Huffaker, G. Park, Z. Zou, O.B. Shchekin, D.G. Deppe, Appl. Phys. Lett. 73 (1998) 2564.
[3] K. Mukai, Y. Nakata, K. Otsubo, N. Yokoyama, H. Ishikawa, Appl. Phys. Lett. 76 (2000) 3349.
[4] J. Bloch, J. Shah, W.S. Hobson, J. Lapata, S.N.G. Chu, Appl. Phys. Lett. 75 (1999) 2199.
[5] K. Nishi, H. Saito, S. Shigou, J. Lee, Appl. Phys. Lett. 74 (1999) 1111.
[6] A. Passaseo, G. Maruccio, M. De Vittorio, R. Rinaldi, R. Cingolani, Appl. Phys. Lett. 78 (2001) 1382.
[7] N.-T. Yeh, T.-E. Nee, J.-I. Chyi, T.M. Hsu, C.C. Huang, Appl. Phys. Lett. 76 (2000) 1567.
[8] M. Fischer, M. Reinhardt, A. Forchel, Electron. Lett. 36 (2000) 1208.
[9] D.A. Livshits, A.Yu. Egorov, H. Riechert, Electron. Lett. 36 (2000) 1381.
[10] M.R. Gokhale, P.V. Studenkov, J. Wei, S.R. Forrest, IEEE Photonics Technol. Lett. 12 (2000) 131.
[11] M. Sopanen, H.P. Xin, C.W. Tu, Appl. Phys. Lett. 76 (2000) 994.
[12] T. Hakkarainen, J. Toivonen, M. Sopanen, H. Lipsanen, Appl. Phys. Lett. 79 (2001) 3932.
[13] T. Hakkarainen, J. Toivonen, M. Sopanen, H. Lipsanen, J. Crystal Growth 234 (2002) 631.