ELSEVIER

Journal of Crystal Growth 235 (2002) 60–64

JOURNAL OF CRYSTAL GROWTH

www.elsevier.com/locate/jcrysgro

Photoluminescence of InAs self-organized quantum dots on (0 0 1)InP substrate with GaAs interlayer

Xinqiang Wang[a], Guotong Du[a], Jingzhi Yin[a], Mei Li[b], Mingtao Li[a], Yi Qu[a,b], BaoXue Bo[a,b], Shuren Yang[a,*]

[a] *Department of Electronics and Engineering, State Key Lab on Integrated Optoelectronics, Jilin University, Changchun 130023, People's Republic of China*

[b] *National Key Laboratory on High Power Semiconductor Lasers, Changchun Institute of Optics and Fine Mechanics, Changchun 130022, People's Republic of China*

Received 24 September 2001; accepted 15 October 2001
Communicated by M. Schieber

Abstract

In this paper, InAs self-organized quantum dots (QDs) were deposited on (0 0 1)InP substrate with and without a GaAs interlayer by low pressure metalorganic chemical vapor deposition. An atomic force microscope image showed that InAs QDs arranged regularly on the GaAs interlayer. Comparison between photoluminescence (PL) spectra of InAs QDs with and without GaAs interlayer indicated that larger area density and much narrower size distribution of InAs QDs were obtained by inserting the GaAs interlayer. The area density of InAs QDs increased while the size distribution hardly changed when the thickness of InAs increased from 2.5 to 4 ML (monolayer). However, when the thickness of InAs increased to 6 ML, the mean size of InAs QDs increased while the area density of InAs QDs decreased because of the coalescence of QDs. PL spectra with different thickness of GaAs interlayer indicated that the largest density of InAs QDs could be obtained when the thickness of GaAs interlayer was 3 nm.

PACS: 68.65.+g; 78.20.e; 07.79.Lh; 61.82.FK

Keywords: A1. Photoluminescence; A3. Metalorganic chemical vapor deposition; B2. Semiconducting III–V materials

1. Introduction

Recently, there is extensive research performed on the fabrication of materials and devices of self-organized quantum dots (QDs) via Stranski–Krastanow (SK) growth mode [1–4], which is induced by relatively large mismatch between the epitaxial layer and substrate. Due to the small size of these QDs, they provide the ultimate quantum system with three-dimensional (3D) carrier confinement resulting in zero-dimensional (0D) density of states. It is predicted that drastic improvement in laser characteristics such as the increase of quantum efficiency and thermal stability and the reduction of the threshold current will be realized with this unique feature of quantum

*Corresponding author. Tel.: +86-431-8922331-3475; fax: +86-431-8964939.
E-mail address: ysr@mail.jlu.edu.cn (S. Yang).

0022-0248/02/$ - see front matter
PII: S0022-0248(01)01795-X

dot. In the experiments, it has been shown that lasers based on QDs had lower threshold current density and higher characteristic temperature in comparison to quantum well lasers. Injection lasers containing InAs and InGaAs QDs embedded in a GaAs and AlGaAs matrix have been successfully fabricated as predicted [5,6]. However, the emitting wavelength for GaAs based QDs can scarcely exceed 1.3 μm [7], which restricts the applications in optical fiber communication systems. It is desirable to fabricate QDs lasers with the wavelength of 1.3–1.55 μm, which can be used in practice. It has been reported that InAs QDs grown on an InP substrate emitted at around 1.55 μm [8–11]. Furthermore, the effective masses of the carriers in the strained InAs quantum structures grown on InP are smaller than those grown on GaAs, which will be beneficial to improve the thermal stability of the devices. However, it is very difficult to obtain InAs QDs on InP with regular arrangement and uniform size. In our study, a thin tensile GaAs layer was used as nucleation site of InAs QDs. We analyzed the formation behaviors of InAs islands without InP capping layer by atomic force image [12]. In this paper, the photoluminescence (PL) properties of InAs QDs at different temperature, excitation power, thickness of InAs corresponding layer and GaAs interlayer were studied. We obtained optimal thickness of GaAs interlayer and found that the intensity of emission of InAs QDs was increased while the FWHM value became narrower after we inserted optimized thin GaAs interlayer. This demonstrated that the area density of InAs QDs became higher and the distribution of InAs QDs became much uniform. The emissions from the ground state and excited state were also observed in PL spectra.

2. Experiment

The samples under investigation were deposited on (0 0 1)InP substrate with trimethylindium (TMIn), trimethylgallium (TMGa), pure AsH_3 and PH_3, 10% in H_2 as precursors. The total pressure in the reactor was kept at 1.01×10^4 Pa and the total gas flow rate was 6 l/min with Pd-purified hydrogen as carrying gas. The V/III ratios were 240 for InP, 80 for GaAs and 260 for InAs. An InP buffer layer (about 0.2 μm) was first grown at 600°C after thermal etching which was performed at 650°C for 5 min under the protection of PH_3, then the growth temperature was reduced to 500°C to deposit thin GaAs layer and InAs QDs layer. After that, about 100 nm InP capping layer was grown at 500°C and then the sample was cooled down to 300°C under the protection of PH_3 and at last the sample was cooled down to room temperature. Samples without GaAs layer were also deposited to make comparisons. To the sample for atomic force microscope (AFM) measurement, it was cooled down to room temperature under the protection of AsH_3 after the growth of InAs QDs layer. The flux of TMIn, TMGa, PH_3 and AsH_3 did not change in the whole experiment procedure. The growth rate of InAs was about 0.2 ML(monolayer)/s.

The AFM analysis was performed with Nanoscope IIIa with normal silicon nitride tip in contact mode. The PL experiments have been performed by PL 9000 system with an Ar ion laser (488 nm) for the sample excitation at a temperature range of 10–300 K.

3. Results and discussion

Fig. 1 showed a three-dimensional AFM image of InAs islands on InP with 3 nm GaAs interlayer. The image size was 789 nm × 789 nm.The corresponding thickness of InAs layer was 6 ML. We could clearly see that InAs QDs arranged along two orthogonal directions. It was well known that InAs QDs arranged randomly on InP substrate. According to the lattice constant of GaAs and InP, the GaAs layer undertook about 3.8% tensile strain on InP, which was also demonstrated by Raman spectra [13]. We hereby used a thin tensile GaAs layer to provide the nucleation site of InAs QDs. The detail analysis of AFM characteristics was reported elsewhere [12].

Fig. 2 showed 10 K PL spectra of InAs QDs on InP substrate and on GaAs/InP under the same growth condition. The thickness of GaAs interlayer was 3 nm. The stronger intensity of PL peak

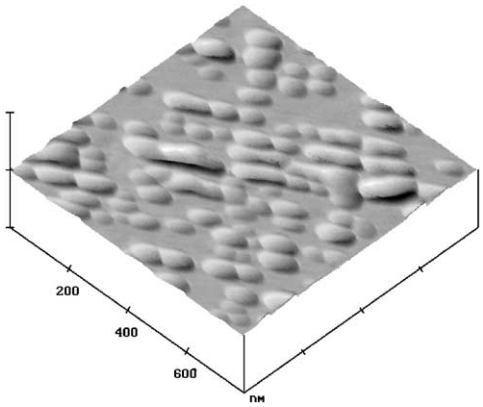

Fig. 1. AFM image of InAs QDs with GaAs interlayer. The image size is 789 nm × 789 nm.

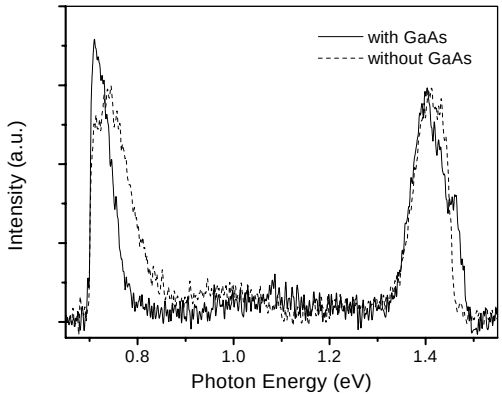

Fig. 2. PL spectra of InAs QDs with GaAs interlayer and without GaAs interlayer at 10 K.

of InAs QDs on GaAs/InP in comparison to that on InP indicated higher area density of InAs QDs. The PL peaks at 1.404 and 1.464 eV in Fig 2. were ascribed to InP layer and GaAs interlayer, respectively. Since the thickness of GaAs was smaller than the critical value, it endured tensile stress. Therefore, the bandgap of tensile GaAs was smaller than that of GaAs bulk [14]. The center peak of PL of InAs QDs on InP lied at 0.744 eV while that on GaAs/InP lied at 0.710 eV. The emission peak of InAs QDs showed relatively large red-shift (34 meV) after we inserted a thin tensile GaAs layer. The reason was the larger size of InAs QDs formed on GaAs interlayer. The FWHM of InAs QDs on GaAs/InP is 45 meV, which is nearly

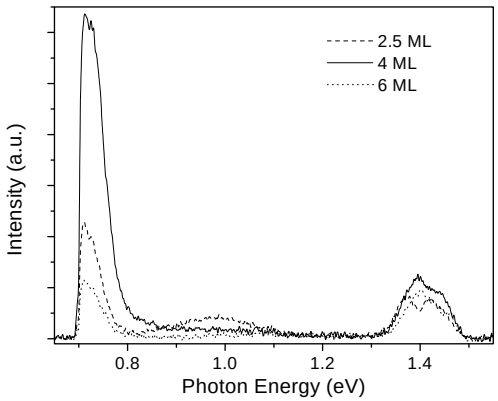

Fig. 3. PL spectra of InAs QDs with GaAs interlayer under different InAs coverage at 10 K.

half of that of InAs QDs on InP, 86 meV. This indicated that the size of InAs QDs became more uniform when the GaAs layer was inserted. From the spectrum of InAs QDs on GaAs/InP, we could find that it was not a Gauss line. This was ascribed to the excited state emission or the emission due to the different size of InAs QDs [15].

Fig. 3 showed PL spectra of InAs QDs on GaAs/InP with different InAs coverage at 10 K. The thickness of InAs were 2.5, 4 and 6 ML, respectively. The emission from 0.689 to 0.827 eV originated from InAs QDs. As shown in this figure, the sample with 4 ML InAs coverage showed the highest PL intensity indicating the largest area density of InAs QDs. The FWHM value of sample with 4 ML was 52 meV while those with 2.5 and 6 ML were 43 and 44 meV, respectively. This showed that the size discrepancy of InAs QDs was the largest when the InAs thickness was 4 ML. We could find two peaks from QDs emission at around 0.713 and 0.725 eV. The peak at 0.713 eV was due to ground state emission while that at 0.725 eV was ascribed to the emission from ground state to excited state. This was confirmed by PL spectra of InAs QDs with different excited power as shown in Fig. 4. The excited state transition became dominant when the pumped power increased to 30 mW. On the contrary, the ground state transition was dominant at pumped power of 5–20 mW. The emission from wetting layer was observed at samples with 2.5 and 6 ML InAs coverage at about 0.976 eV. The reason why

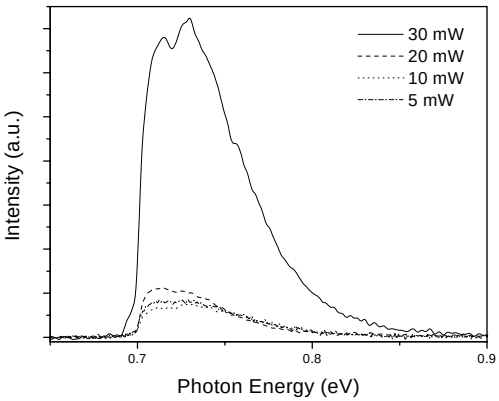

Fig. 4. PL spectra of InAs QDs with GaAs interlayer under different pumped power.

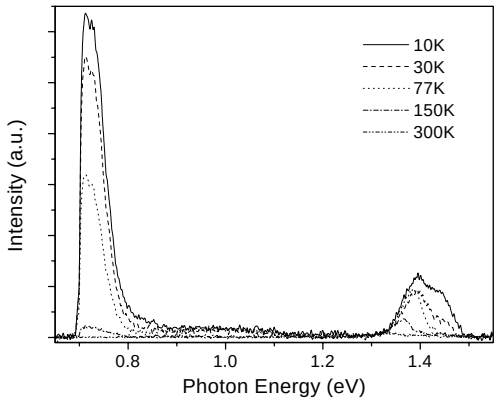

Fig. 5. PL spectra of InAs QDs with GaAs interlayer at different temperature.

we did not find the emission of InAs wetting layer at samples with 4 ML InAs coverage was that the intensity of InAs quantum dots was much stronger than that from wetting layer. In detail analysis of Fig. 3, we could find that the emission peak from ground states of InAs QDs with 2.5 and 4 ML InAs lied at 0.713 eV while that with 6 ML InAs coverage lied at 0.711 eV. This slight redshift was due to the larger size of InAs QDs. When the thickness of InAs increased from 2.5 to 4 ML, the number of InAs quantum dots increased drastically while the size distribution of InAs QDs did not change. Then, when the thickness of InAs increased to 6 ML, the size of InAs QDs increased and some QDs coalesced. Therefore, the density of InAs QDs decreased and the emission intensity became weaker. Meanwhile, the position of emission peak shifted to low energy side because of the increase of InAs QDs size.

Fig. 5 showed the PL spectra of InAs QDs on InP with GaAs interlayer at different temperature with 4 ML InAs coverage. With the increase of temperature, we could see that the PL intensity decreased while the PL peak showed slight redshift. This coincided with that of InAs QDs on InP in previous report [16]. We got that the FWHM value hardly changed with the temperature from this figure.

The PL spectra of InAs QDs with different thickness of GaAs interlayer were investigated as shown in Fig. 6. The thickness of InAs was 4 ML to each sample. We could obtain that the sample

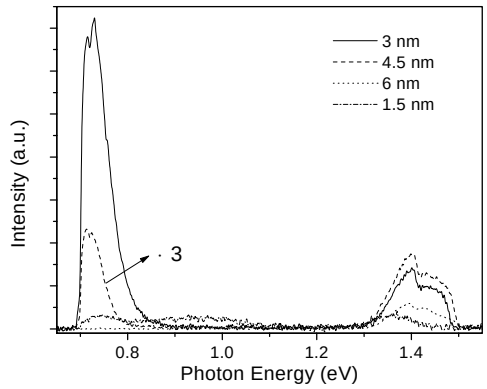

Fig. 6. PL spectra of InAs QDs with different thickness of GaAs interlayer at 10 K.

with 3 nm GaAs interlayer showed the strongest intensity indicating the largest QDs area density. The FWHM value of sample with 3 nm GaAs interlayer was 58 meV, which is larger than 47 meV of the sample with 4.5 nm GaAs interlayer. This implied that we obtained high area density of InAs QDs but relatively broad size distribution using 3 nm GaAs interlayer.

4. Conclusion

We reported the formation of InAs QDs with regular arrangement on InP using a thin GaAs interlayer. AFM analysis showed that InAs QDs arranged along two orthogonal directions. The

comparison between PL spectra of InAs QDs on GaAs/InP and on InP showed that the emission intensity was stronger and the FWHM was much smaller after we inserted the GaAs layer. This indicated that we got higher area density and more uniform size distribution of InAs QDs. We found that the density of InAs QDs increased sharply and the size distribution hardly changed when the thickness of InAs increased from 2.5 to 4 ML. However, when the thickness of InAs increased to 6 ML, the size of InAs QDs increased and the density of InAs QDs decreased due to QDs coalescence. The emissions from the ground states and excited states were both found in PL spectra and confirmed by PL spectra at different excitation power. PL spectra at different temperature showed relatively small redshift of InAs QDs emission peak with the increase of temperature. We got the largest area density of InAs QDs when the thickness of GaAs interlayer was 3 nm.

Acknowledgements

This work was supported by the National Natural Science foundation of China (NSFC) under Grant No. 69976012.

References

[1] A. Moritz, R. Wirth, A. Hangleiter, A. Kurtenbach, K. Eberi, Appl. Phys. Lett. 69 (1996) 212.
[2] F. Heinrichsdorff, Ch. Ribbat, M. Grundmann, D. Bimberg, Appl. Phys. Lett. 76 (2000) 556.
[3] E.C. Le Ru, P.D. Siverns, R. Murray, Appl. Phys. Lett. 77 (2000) 2446.
[4] D. Pan, E. Towe, Electron. Lett. 34 (1998) 1883.
[5] N. Kirstaedter, N.N. Ledentsov, M. Grundmann, D. Bimberg, V.M. Ustinov, S.S. Ruvimov, M.V. Maximov, P.S. Kop'ev, Zh.I. Alferov, U. Richter, P. Werner, U. Gosele, J. Heydenreich, J. Electron. Lett. 30 (1994) 1416.
[6] K. Kamath, P. Bhattacharya, T. Sosnowski, T. Norries, J. Philips, Electron. Lett. 32 (1996) 1374.
[7] J. Bloch, J. Shah, L.N. Pfeiffer, K.W. West, S.N.G. Chu, Appl. Phys. Lett. 77 (2000) 2545.
[8] B. Lambert, A. LeCorre, V. Drouot, H. L'Haridon, S. Loualiche, Semicond. Sci. Technol. 13 (1998) 143.
[9] M. Tashinen, M. Sopanen, H. Lipsanen, J. Tulkki, T. Tuomi, J. Ahopelto, Surf. Sci. 376 (1997) 60.
[10] W.G. Jeong, P.D. Dapkus, U.H. Lee, J.S. Lee, J.S. Yim, D. Lee, B.T. Lee, Appl. Phys. Lett. 78 (2001) 1171.
[11] A. Ruda, R. Houdre, J.F. Carlin, M. Ilegems, J. Crystal Growth 136 (1994) 278.
[12] X. Wang, G. Du, Z. Jin, M. Li, J. Yin, Z. Li, S. Liu, S. Yang, J. Vac. Sci. Technol. B 18 (2000) 2523.
[13] X. Wang, Z. Li, G. Du, J. Yin, M. Li, W. Lu, S. Yang, Opt. Quant. Electron., to be published.
[14] E. Herbert Li, Physica E 5 (2000) 215.
[15] Y.C. Zhang, C.J. Huang, F.Q. Liu, B. Xu, D. Ding, W.H. Jiang, Y.F. Li, X.L. Ye, J. Wu, Y.H. Chen, Z.G. Wang, J. Crystal Growth 219 (2000) 199.
[16] Q.D. Zhuang, S.F. Yoon, H.Q. Zheng, K.H. Yuan, J. Crystal Growth 216 (2000) 57.