ELSEVIER

Journal of Crystal Growth 188 (1998) 383–386

JOURNAL OF **CRYSTAL
GROWTH**

Self-organized InAs/GaAs quantum dots grown on (1 0 0) misoriented substrates by molecular beam epitaxy

Ming-Chin Chen^a, M.C. Harris Liao^b, Hao-Hsiung Lin^{a,*}

^a *Department of Electrical Engineering, Room 419, National Taiwan University, Taipei, Taiwan, ROC*

^b *Department of Physics, National Taiwan University, Taipei, Taiwan, ROC*

Abstract

In this study, self-organized InAs quantum dots (QDs) were grown on (1 0 0) GaAs substrates with a 7° off-cut towards the (1 1 0) plane by using molecular beam epitaxy. QD with 2 ML nominal thickness grown on the vicinal substrate shows a 8.5 K photoluminescence line width of 27 meV and a dot density of $3 \times 10^{11}/\text{cm}^2$. © 1998 Elsevier Science B.V. All rights reserved.

PACS: 68.55.Bd; 68.55.Jk; 78.55.Cr

Keywords: InAs; GaAs; Quantum dots; Molecular beam epitaxy; Misoriented substrate

1. Introduction

Recently, strain-induced self-organized In(Ga)As/GaAs quantum dots (QDs) have been intensely studied because these QDs show an efficient carrier confinement which can be used for the realization of novel optoelectronic devices like quantum dot lasers. Such QD lasers with low threshold current density and high characteristic temperature (T_0) have been demonstrated [1]. For practical applications in optoelectronic devices, QDs with high density and good uniformity are necessary to achieve

the desired active volume. Several groups [2–4] have made great efforts on the growth conditions including substrate temperature, V/III flux ratio, InAs growth rate and substrate orientation to achieve these requirements. Recent study on the effect of substrate orientation [3] shows that the QDs grown on (7 1 1)B substrate have better quantum efficiency than those on (5 1 1)B and (1 0 0) substrates. It implies that a slight misorientation for (1 0 0) substrate may improve the uniformity of the QDs. In our study, (1 0 0) GaAs substrates with a 7° off-cut towards the (1 1 0) plane were adopted. QD with 2 ML nominal thickness grown on this vicinal substrate shows a 8.5 K photoluminescence linewidth of 27 meV and a dot density of $3 \times 10^{11}/\text{cm}^2$.

* Corresponding author. Tel.: +886 2 363 52 51, ext. 419; fax: +886 2 363 24 42; e-mail: hhl@cc.ee.ntu.edu.tw.

2. Experimental procedure

In this study, QD structures were grown by using a VG V80H MBE system. (1 0 0) semi-insulating GaAs substrates misoriented by 7° towards the (1 1 0) plane were used. The growth procedure included a 200 nm thick buffer layer grown at 620°C , an InAs layer deposited at 490°C , a 10 nm GaAs layer grown at 490°C to avoid In segregation, and a 40 nm GaAs capping layer grown at 620°C . The growth rate and V/III beam equivalent pressure ratio of InAs layer were 0.25 ML/s and 90, respectively. Four samples with nominal InAs thickness of 1, 2, 5 and 10 ML were grown. After growth, photoluminescence (PL) measurement was used to characterize these samples.

3. Results and discussions

Fig. 1 shows the 8.5 K low-temperature PL spectra of the QD samples. As we can see, the PL peak energy decreases as the nominal thickness increases except that of the sample with 10 ML thickness. The PL spectrum of the sample with 1 ML thickness is with the highest peak energy of 1.46 eV and the smallest full width at half-max-

Fig. 1. 8.5 K PL spectra of samples with various InAs nominal thickness, 1, 2, 5 and 10 ML.

imum (FWHM) of 6.6 meV, which indicates that three dimensional growth has not yet started on this sample. The PL behavior is attributed to the quantum well behavior of its two-dimensional wetting layer. The sample with 2 ML thickness shows the strongest PL intensity, and its PL FWHM is only 27 meV which is among the narrowest FWHMs that have been reported in literature. It implies that the dot size distribution is highly uniform. The PL peak energies of the samples with 5 and 10 ML thickness red-shift to 1.22 and 1.27 eV, respectively. Their FWHMs become broader, and the intensities degrade seriously. These results indicate that the QDs on these two samples have larger size and worse uniformity than the sample with 2 ML thickness. The seriously degraded PL intensities also reveal that misfit dislocations may exist in these samples, otherwise the PL intensities should be further improved because of the more InAs monolayers deposited in these samples. It is interesting that the peak energy of the sample with 10 ML thickness is higher than that of the sample with 5 ML thickness. The intensity around its peak energy is even higher than that of the 5 ML sample. Because the number of InAs monolayers is two-times larger, having a stronger PL intensity around the peak energy is not unreasonable for the 10 ML sample. However, it also reveals that, during the end of the InAs three-dimensional growth on this sample, the misfit dislocation on the large size dots probably prevents the further size enlargement and new dots with small size are forcedly generated. For this sake, the PL peak shows the asymmetric shape as can be seen in the figure.

The wavelength-integrated PL intensity as a function of thermal energy, kT , is shown in Fig. 2. The thermal quenching energy and activation energy are extracted according to the following equation of PL intensity;

$$I(T) = \frac{I_0}{1 + \exp\left(\frac{\Delta E}{E_Q} - \frac{\Delta E}{kT}\right)},$$

where I_0 is the intensity at 0 K, ΔE is the activation energy from exciton radiative state to non-radiative state, and E_Q is the thermal quenching energy

defined as the thermal energy when the intensity drops to half of I_0 . The fitted results are summarized in Table 1. As shown in the table, the thermal quenching and activation energy of the 1 ML sample are 2 and 27 meV, respectively. The activation energy is mainly due to the binding energy of excitons, which is much larger than those in bulk GaAs and InAs because of the quantum confinement effect. In fact, the value is close to those of InGaAsP/InP multiple quantum well structures grown in our laboratory with the values around 32–40 meV for various well thicknesses. This comparison confirms that the structure on the 1 ML sample is not quantum dots but a wetting layer as

Fig. 2. Plots of wavelength-integrated PL intensity as a function of thermal energy for samples with InAs nominal thickness of 1, 2, 5 and 10 ML.

Table 1

Thermal quenching energy (E_Q) and activation energy (ΔE) for samples with different InAs nominal thickness

Nominal thickness (ML)	Thermal quenching energy E_Q (meV)	Activation energy ΔE (meV)
1	2	27
2	8	135
5	5	54
10	3	34

discussed previously in this section. The 2 ML QD sample shows much larger thermal quenching and activation energy, the values are as high as 8 and 135 meV, respectively. This large activation energy demonstrates the exciton binding energy enhancement due to the three-dimensional confinement in the quantum dots. For the 5 and 10 ML samples, the activation energy drops to 54 and 34 meV, respectively. The degradation may be due firstly to the size enlargement which reduces the quantum confinement effect on the excitons, and secondly to the generation of nonradiative defects.

Fig. 3 shows the PL peak energy as a function of temperature for all samples. For comparison, the InAs band gap calculated using the Varshni relation [5] with the data of 0.6 eV strained band gap at 0 K [6] is also plotted in the figure. As can be seen, the trends of the 1 and 2 ML samples are close to that of InAs band gap. The coincidence of the 2 ML sample confirms its good uniformity. However, the peak energies of the 5 and 10 ML samples decrease much faster than the Varshni relation of strained InAs band gap, which means that the PL intensities of these two samples are dominated by different dots at different temperatures. From the plot, it is clear that the small dots dominate the

Fig. 3. Plots of PL peak energy as a function of temperature. Besides the samples, strained InAs band gap is also plotted for comparison.

Fig. 4. AFM image on the surface of the sample with 2 ML InAs nominal thickness.

peak at low temperature. When the temperature rises, the large dots gradually take over. The red-shift may result from the carrier transition from the small dots to the large dots at high temperature. The reason for the dominance of the large dots at high temperature is that they are quenched slower than the small dots.

Fig. 4 shows the AFM image on the surface of the 2 ML sample. The QD size is with good uniformity, which resulted in smaller PL line width of

27 meV, and the dot density is as high as $3 \times 10^{11}/\text{cm}^2$. As shown in the figure, the QDs sit along the step-edge direction of the vicinal plane.

4. Conclusion

Self-organized InAs QDs grown by molecular beam epitaxy on (1 0 0) GaAs substrates with a 7° off-cut towards the (1 1 0) plane have been studied. The sample with 2 ML InAs nominal thickness show an excellent PL FWHM of 27 meV at 8.5 K. The dot density of this sample measured by atomic force microscopy (AFM) is as high as $3 \times 10^{11}/\text{cm}^2$.

References

- [1] 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, P. Werner, U. Gösele, J. Heydenreich, *Electron. Lett.* 30 (1994) 1416.
- [2] D. Bimberg, N.N. Ledentsov, M. Grundmann, N. Kirstaedter, O.G. Schmidt, M.H. Mao, V.M. Ustinov, A.Yu. Egorov, A.E. Zhukov, P.S. Kop'ev, Zh.I. Alferov, S.S. Ruvimov, U. Gösele, J. Heydenreich, *Phys. Stat. Sol. B* 194 (1996) 159.
- [3] D.I. Lubyshev, P.P. Gonzalez-Borrero, E. Marega Jr., E. Petitprez, P. Basmaji, *J. Vac. Sci. Technol. B* 14 (1996) 2212.
- [4] A. Madhukar, Q. Xie, P. Chen, A. Konkar, *Appl. Phys. Lett.* 64 (1994) 2727.
- [5] Y.P. Varshni, *Physica* 34 (1967) 149.
- [6] H.Q. Hou, C.W. Tu, *J. Appl. Phys.* 75 (1994) 4673.