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Molecular beam epitaxial growth of high quality InAs/GaAs quantum dots for 1.3-μm quantum dot lasers*

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Systematic investigation of InAs quantum dot (QD) growth using molecular beam epitaxy has been carried out, focusing mainly on the InAs growth rate and its effects on the quality of the InAs/GaAs quantum dots. By optimizing the growth rate, high quality InAs/GaAs quantum dots have been achieved. The areal quantum dot density is 5.9×10^{10} cm^{-2}, almost double the conventional density (3.0×10^{10} cm^{-2}). Meanwhile, the linewidth is reduced to 29 meV at room temperature without changing the areal dot density. These improved QDs are of great significance for fabricating high performance quantum dot lasers on various substrates.

Keywords: quantum dots, growth rate, dot density, linewidth

PACS: 81.05.Ea, 81.07.Ta, 81.15.Hi, 81.70.–q **DOI:** 10.1088/1674-1056/28/7/078104

1. Introduction

In recent years, 1.3-μm quantum dot (QD) lasers have become a key component for low power light sources in optical telecommunications, garnering much attention.[1–3] In contrast to the quantum well laser diode and heterojunction laser diode, this type of laser has advantages of extremely low threshold current,[4–6] reduced temperature dependence,[2,7] chirp-free modulation,[8] and high differential efficiency.[6,9] In the field of semiconductor QD lasers, InAs/GaAs are among the more typical materials used. Up to now, the studies on InAs/GaAs QD lasers have achieved excellent progress.[10–13] However, systematic research on the dot density and size uniformity control of QDs is not widely conducted. The growth process of QDs has a significant influence on the dot density and size uniformity of QDs, thereby affecting the performance of the laser.[14] Thus, it is essential to optimize the growth parameters for producing high quality quantum dots.

The growth of InAs on GaAs has a tendency to form islands due to the large lattice mismatch, almost 7.16%, which results in the epitaxial growth transitions from two-dimensional layered growth to three-dimensional island growth. This is the Stranski–Krastanow (S–K) growth mode, which is suitable here for the proposed heterojunction material system with a mismatch in lattice constants but a low interfacial energy.[15] The growth quality of the QDs (dot density and size uniformity) has significant influence on the performance of the final device, as well as affecting the intermediately fabrication processes, thus it is very important to ensure the high quality of QDs in the growth stage.[16,17]

Various investigations of optimizing the parameters have been reported to obtain high quality QDs. Metal–organic chemical vapor deposition (MOCVD) is one of the typical deposition techniques employed.[18,19] However, it is difficult to fabricate arsenic based high performance QD lasers using MOCVD.[20,21] Molecular beam epitaxy (MBE) is a more suitable method, where the interruption growth mode of QDs,[22] growth temperature,[23] and multistacking QD layers[24,25] are methods proposed to enhance the surface dot density. While these do improve the dot density, $(4–5)\times 10^{10}$ cm^{-2}, introduction of singular large QDs is also seen, which then degrades the QD uniformity.[22,23] For further enhancement of the QD quality, this introduction of singular large QDs needs to be suppressed. Various methods such as increasing the surface adatom mobility,[26] introducing a strain reducing layer (SRL),[27] and optimizing the growth rate[14,16,28,29] have been investigated for improving the QD size uniformity. By introducing the strain reducing layer, the linewidth was reduced to 21 meV while the density only achieved 1.0×10^{10} cm^{-2}.[27] A recent study by Liu's group systematically improved the dot-height uniformity of QD, obtaining the linewidth of 30 meV with the density of 4.5×10^{10} cm^{-2} and 42 meV with the density of 5.8×10^{10} cm^{-2}.[29] Thus far, few comprehensive investigations for improving both dot density and size uniformity have been done. We aim to optimize the growth parameters to ob-

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tain high dot density and high size uniformity.

The growth rate of QDs is shown to affect not only the density and uniformity of materials, but also their photoluminescence (PL): if the density of QDs is too high, singular large QDs are formed, resulting in decreased PL intensity and broadened linewidth. In this paper, the influence that the growth rate has on the quality of InAs QDs (on GaAs substrates) via MBE is systematically investigated, with the optimized growth rate determined. Atomic force microscope (AFM) and PL measurements are conducted on the bare QD demonstrating the significant influence that the growth rate has on the QD density, size uniformity, and the optical properties.

2. Experiment

Figure 1 shows the structure for the active region of the quantum dot laser. A GaAs buffer layer with a thickness of 300 nm was grown on the substrate, followed by the active region with three layers of InAs/GaAs QDs. An uncapped QD layer was grown on the surface for AFM measurement. For the active region, a stack of 2.3 monolayer (ML) InAs/5 nm $In_{0.15}Ga_{0.85}As$/40 nm GaAs was grown. To achieve ground state lasing rather than the excited state, the active region adopted a multi-layer quantum dot structure to increase the effective number of QDs for an enhanced luminous intensity.[30] At the same time, the thickness of the QD SRL cannot be too thin to prevent the interaction between QDs of the adjacent layers.[31]

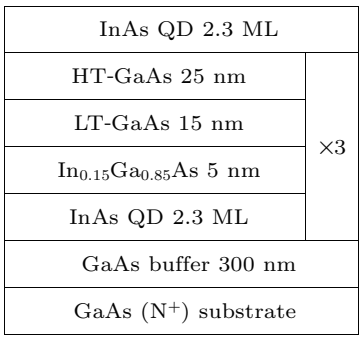


Fig. 1. Structure for the active region of the quantum dot laser.

All samples were grown on GaAs (001) n-type substrates using the Gen 930 MBE system from Veeco Instruments equipped with reflective high-energy electron diffractometer (RHEED). The sample was loaded into the MBE chamber with molybdenum adapting plates and in the introduction chamber/buffer chamber, moisture, carbon dioxide, and other impurity on the surface were removed by degassing at a temperature of 200 ℃/420 ℃. It was then transferred to the growth chamber for oxide desorption at 650 ℃ under As_2-overpressure. Real-time reciprocal space image of the substrate surface was shown through RHEED (Figs. 2(a) and 2(b)). Once cleaned, a GaAs buffer was grown at 600 ℃ with RHEED for *in situ* growth monitoring. The (2×4) reconstruction of GaAs can be observed in Figs. 2(c) and 2(d).

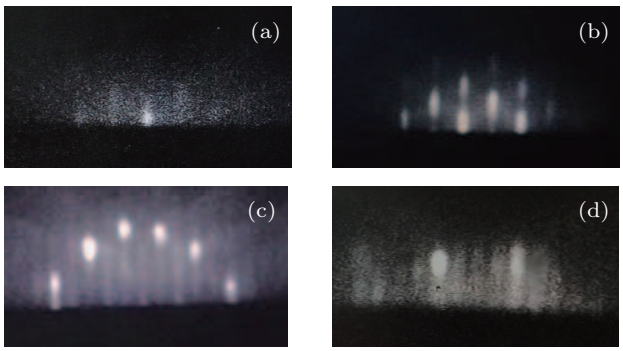


Fig. 2. RHEED images of the substrate surface: (a) the start of oxide desorption, (b) oxide desorption complete, (c) (2×4) reconstruction of [110] direction, and (d) (2×4) reconstruction of $[1\bar{1}0]$ direction.

Finally, other layers of the active region (as shown in Fig. 1) were grown. The variable in the growth process was the QD growth rate, 0.04 ML/s, 0.06 ML/s, and 0.08 ML/s, respectively. All other parameters were kept identical, as shown in Table 1.

Table 1. The growth parameters of the sample.

Growth parameters	Sample A	Sample B	Sample C
Growth temperature/℃	525	525	525
Growth rate of QD/ML·s^{-1}	0.04	0.06	0.08
Deposition amount/ML	2.3	2.3	2.3
V–III ratio	20	20	20

3. Results and discussion

The AFM images of the uncapped surface QDs in different growth rates are shown in Fig. 3. The raised dots indicate that the InAs islands are fine grown with almost no defects. As the growth rate increases, the density of the QDs initially increases and then decreases, 4.2×10^{10} cm^{-2}, 5.9×10^{10} cm^{-2}, and 2.8×10^{10} cm^{-2}, respectively. In Fig. 3(a), there are two large QDs, while figures 3(b) and 3(c) show areas of uniform QDs, without visible large QDs. The AFM measurement results are listed in Table 2. It is observed that the dot density of sample B reached 5.9×10^{10} cm^{-2} without visible large QDs, which is almost double the conventional density $(3.0\times10^{10}$ cm$^{-2})$.[11,32] It is worth noting that in 2018 researchers from the University of Tokyo produced QDs with a density of 5.1×10^{10} cm^{-2}; however, the QD quality was degraded by the presence of large QDs.[33]

The nucleation sites for InAs remain mostly the same regardless of the growth rate. However, under lower growth rates, the relative distance between nucleates is larger (nucleates are smaller), whereas the relative distance between nucleates grown with higher rates is shorter (nucleates are larger).

Starting at a low growth rate, the density/uniformity of the QD array is low due to some nucleates growing to islands while others remain very small. As the growth rate increases, the QD array quality increases: each QD is well grown thus the density and uniformity are improved. However, as the growth rate is further increased, the QD array quality decreases again as the islands cluster and fuse to become large QDs. Therefore, there is an optimized growth rate producing high uniformity and dense QD array.

Table 2. Properties of QDs with different growth rates.

Sample	Growth rates/ML·s^{-1}	QD density /10^{10} cm^{-2}	Defects
A	0.04	4.2	two large QDs
B	0.06	5.9	without visible large QDs
C	0.08	2.8	without visible large QDs

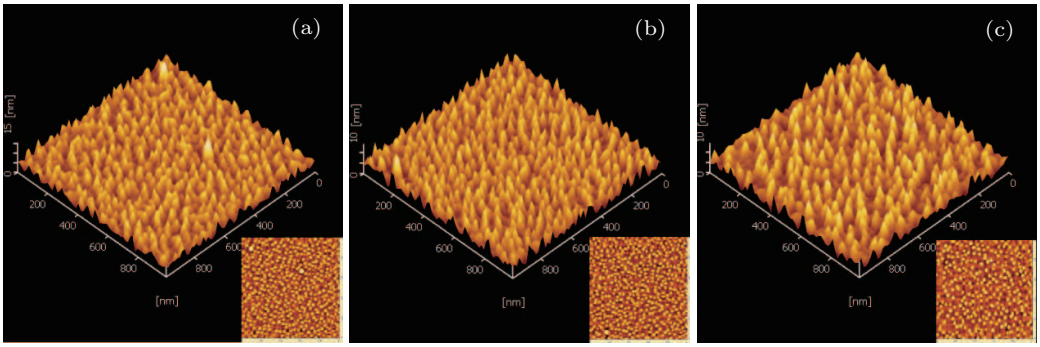


Fig. 3. The 1 μm ×1 μm AFM images of InAs/GaAs QDs: (a) sample A, (b) sample B, and (c) sample C.

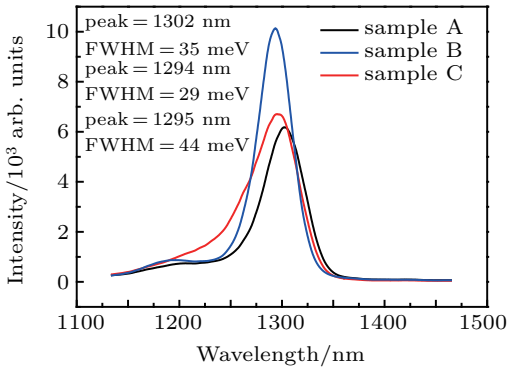


Fig. 4. Room-temperature PL spectra of samples A, B, and C.

PL measurements under room temperature (RT) were also conducted for the samples, as shown in Fig. 4. The PL spectrum is one of the most common approaches for detecting the physical properties and quality of semiconductor materials. The main peak of the PL spectrum corresponds to the inter-band radiation recombination of the QD ground state. The higher the carrier concentration of the ground state, the stronger the main peak in the PL spectrum. Additionally, the full width at half maximum (FWHM), namely, the linewidth, of the spectrum represents the size uniformity of QDs, the narrower the linewidth, the better the uniformity. Sample B, grown at the rate of 0.06 ML/s, exhibited the strongest PL intensity (1.64 times higher than that of sample A and 1.51 times higher than that of sample C). The linewidths are 29 meV, 35 meV, and 44 meV for samples B, A, and C, respectively. The peak positions in the PL spectra were around 1300 nm, consistent with 1.3 μm QD laser lasing requirements. Therefore, sample B, with the strongest PL intensity and narrowest linewidth, is the one showing high size uniformity in comparison to that in Refs. [27] and [29]. The PL results are consistent with the AFM measurements.

4. Conclusion and perspectives

A series of samples grown at varying InAs QDs growth rates were studied systematically. The growth rate of the QDs significantly influenced the quality of the InAs QDs. The optimized growth rate of 0.06 ML/s produced the best QDs in terms of dot density, size uniformity, and PL spectrum. By optimizing the growth rate, an InAs quantum dot density of 5.9×10^{10} cm^{-2}, almost double the conventional density (3.0×10^{10} cm^{-2}), has been achieved. At the same time, sample B, grown at the rate of 0.06 ML/s, exhibited the strongest PL intensity (1.64 times higher than that of sample A and 1.51 times higher than that of sample C) and narrowest linewidth, 29 meV. This process of optimizing the growth rate for producing high quality InAs QDs (high dot density and size uniformity) will serve as a basis for optimizing the growth of high performance 1.3 μm quantum dot laser on various substrates.

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References

[1] Wilk A, Kovsh A R, Mikhrin S S, Chaixa C, Novikovc I I, Maximovc M V, Shernyakovc Yu M, Ustinovc V M and Ledentsov N N 2005 *J.*

Cryst. Growth **278** 335
[2] Tanaka Y, Ishida M, Maeda Y, Akiyama T, Yamamoto T, Song H Z, Yamaguchi M, Nakata Y, Nishi K, Sugawara M and Arakawa Y 2009 *Proceedings of Optical Fiber Communication Conference and National Fiber Optic Engineers Conference*, March 22–26, 2009 San Diego, United States, p. OWJ1
[3] Wang Z, Preble S, Lee C S and Guo W 2015 *Proceedings of Advanced Photonics: Integrated Photonics Research, Silicon and Nanophotonics*, June 27–July 1, 2015 Boston, United States, p. IM4B.4
[4] Tsang W T 1982 *Appl. Phys. Lett.* **40** 217
[5] Hersee S D, Baldy M, Assenat P, Cremoux B D and Duchemin J P 1982 *Electron. Lett.* **18** 870
[6] Liu H Y, Liew S L, Badcock T, Mowbray D J, Skolnick M S, Ray S K, Choi T L, Groom K M, Stevens B, Hasbullah F, Jin C Y, Hopkinson M and Hogg R A 2006 *Appl. Phys. Lett.* **89** 073113
[7] Fathpour S, Mi Z, Bhattacharya P, Kovsh A R, Mikhrin S S, Krestnikov I L, Kozhukhov A V and Ledentsov N N 2004 *Appl. Phys. Lett.* **85** 5164
[8] Saito H, Nishi K, Kamei A and Sugou S 2000 *IEEE Photonic. Tech. L* **12** 1298
[9] Kovsh A R, Maleev N A, Zhukov A E, Mikhrin S S, Vasil'ev A P, Shemyakov Yu M, Maxim M V, Livshits D A, Ustinov V M, Alferov Zh I, Ledentsov N N and Bimberg D 2002 *Electron. Lett.* **38** 1104
[10] Salhi A, Raino G, Fortunato L, Tasco V, Visimberga G, Martiradonna L, Todaro M T, Giorgi M D, Cingolani R, Trampert A, Vittorio M D and Passaseo 2008 *IEEE J. Sel. Top. Quant.* **14** 1188
[11] Tanaka Y, Ishida M, Takada K, Yamamoto T, Song H Z, Nakata Y, Yamaguchi M, Nishi K, Sugawara M and Arakawa Y 2010 *Proceedings of Conference on Lasers and Electro-Optics,* May 16–21, 2010 San Jose, United States, p. CTuZ1
[12] Xu P F, Yang T, Ji H M, Cao Y L, Gu Y X, Liu Y, Ma W Q and Wang Z G 2010 *J. Appl. Phys.* **107** 013102
[13] Su X B, Ding Y, Ma B, Zhang K L, Sh Z, Li J L, Cui X R, Xu Y Q, Ni H Q and Niu Z C 2018 *Nanoscale Res. Lett.* **13** 59
[14] Joyce P B, Krzyzewski T J, Bell G R, Jones T S, Malik S, Childs D and Murray R 2000 *Phys. Rev. B* **62** 10891
[15] Walther T, Cullis A G, Norris D J and Hopkinson M 2001 *Phys. Rev. Lett.* **86** 2381
[16] Nakata Y, Mukai K, Sugawara M, Ohtsubo K, Ishikawa H and Yokoyama N 2000 *J. Cryst. Growth* **208** 93
[17] Ra'ed M H and Eyman T S 2016 *IOSR-JAP* **8** 01
[18] Guimard D, Ishida M, Li L, Nishioka M, Tanaka Y, Sudo H, Yamamoto T, Kondo H, Sugawara M and Arakawa Y 2009 *Appl. Phys. Lett.* **94** 103116
[19] Rajesh M, Bordel D, Kawaguchi K, Faure S, Nishioka M, Augendre E, Clavelier L, Guimard D and Arakawa Y 2011 *J. Cryst. Growth* **315** 114
[20] Li T H, Wang Q, Guo X, Jia Z G, Wang P Y, Ren X M, Huang Y Q and Cai S W 2012 *Phys. E* **44** 1146
[21] Liu H, Wang Q, Chen J, Liu K and Ren X M 2016 *J. Cryst. Growth* **455** 168
[22] Niu Z C, Ni H Q, Fang Z D, Gong Z, Zhang S Y, Wu D H, Sun Z, Zhao H, Peng H L, Han Q and Wu R H 2006 *Chin. J. Semicond.* **27** 482
0253-4177(2006)03-0482-07
[23] Yue L, Gong Q, Cao C F, Yan J Y, Wang Y, Cheng R H and Li S G 2013 *Chin. Opt. Lett.* **11** 061401
[24] Akahane K, Yamamoto N and Tsuchiya M 2008 *Appl. Phys. Lett.* **93** 041121
[25] Akahane K, Matsumoto A, Umezawa T, Yamamoto N and Kawanishi T 2016 *2016 Proceedings of International Semiconductor Laser Conference*, September 12–15, 2016 Kobe, Japan, p. WE46
[26] Yamaguchi K, Yujobo K and Kaizu T 2000 *Jpn. J. Appl. Phys.* **39** L1245
[27] Nishi K, Saito H, Sugou S and Lee J S 1999 *Appl. Phys. Lett.* **74** 1111
[28] Konishi T, Clarke E, Burrows C W, Bomphrey J J, Murray R and Bell G R 2017 *Sci. Rep.* **7** 42606
[29] Liu W S 2013 *J. Alloys Compd.* **571** 153
[30] Akahane K, Yamamoto N and Kawanishi T 2010 *IEEE Photonic. Tech. L.* **22** 103
[31] Wang Z M, Feng S L, Lv Z D, Yang X P, Chen Z G, Song C Y, Xu Z Y, Zheng H Z, Wang F L, Han P D and Duan X F 1998 *Acta Phys. Sin.* **47** 89 (in Chinese)
[32] Li L, Guimard D, Rajesh M and Arakawa Y 2008 *Appl. Phys. Lett.* **92** 263105
[33] Kwoen J, Jang B, Lee J, Kageyama T, Watanabe K and Arakawaet Y 2018 *Opt. Express* **26** 11568
[34] Ji H M, Yang T, Cao Y L, Xu P F, Gu Y X, Ma W Q and Wang Z G 2010 *Chin. Phys. Lett.* **27** 027801