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Optimization of InGaAs Quantum Dots for Optoelectronic Applications

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Abstract: Self-assembled $In_{0.35}Ga_{0.65}As/GaAs$ quantum dots with low indium content are grown under different growth temperature and investigated using contact atomic force microscopy(AFM). In order to obtain high density and high uniformity of quantum dots, optimized conditions are concluded for MBE growth. Optimized growth conditions also compared with these of InAs/GaAs quantum dots. This will be very useful for InGaAs/GaAs QDs optoelectronic applications, such as quantum dots lasers and quantum dots infrared photodetectors.

Key words: InGaAs/GaAs; quantum dot; optimization; MBE; AFM; optoelectronics
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1 Introduction

One basic requirement of self-assembled quantum dot is high density[1], which is essential to the optoelectronic applications, such as quantum dots lasers and quantum dots infrared photodetectors[2~4]. Unless we can obtain high density and high uniformity of quantum dots structures, we cannot have realistic performance of these devices, such as high gain and high quantum efficiency. However, for the more flexible InGaAs/GaAs self-assembled quantum dots, which can have at least one more freedom to engineer energy band than InAs/GaAs, no much higher density and uniformity conditions for molecular beam epitaxy (MBE) are available to our knowledge. Thus the condition of optimization is needed for high density and high uniformity of quantum dots growth for MBE system.

In this article, we optimized the growth conditions of $In_{0.35}Ga_{0.65}As/GaAs$ (001) quantum dots using solid source MBE, and AFM measurements were carried out on all our samples. Through our continuous efforts we obtained much higher density and higher uniformity of quantum dots. We wish our results can be of any help for those concerned with (In, Ga)As/GaAs self-assembling quantum dots system to optimize their QDs growth and improve their device quality.

2 Experiments

Our samples were grown using EPI Gen II MBE system. Several growth conditions have been changed systematically to fully optimize the growth condition for high quality of quantum dots with high density, high uniformity, and higher volume filling factor. Before the growth of quantum dots, a 200nm GaAs buffer layer was firstly grown at the substrate temperature of 580℃ with the As beam flux of 10^{-3}Pa. Then the growth conditions were tuned to the needed conditions with the As valve shutter opened. After the conditions were satisfied, $In_{0.35}Ga_{0.65}As$

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layer was deposited. The InGaAs epilayer deposition was monitored in situ with RHEED (reflection high energy electron diffraction) and the dots formation was confirmed by the pattern transition from streaky to dotty. After the growth was over, the temperature decreased as quickly as it could and with only the As source supplied in order to keep the epilayer shapes for the measurement ofAFM.

The samples were measured by NanoScape IIIa AFM machine using contact mode and analyzed with dedicated software.

3 Results and discussion

Growth temperature, materials deposited, V/ III ratio, and silicon doping were changed for the optimization of growth conditions. The AFM images of all samples are shown here for comparison. AFM is favored for nanoscale research due to its atomic resolution, i. e. about 0.1nm vertically and 1nm horizontally. However, these resolutions are quite sensitive to the tip shape and the history of tip usage so that the size of each measurement is not absolutely comparable. But the density, in our case of quantum dots measurement, is quite accurate for its much larger range scanning, to say 1μm × 1μm. Thus in our results, we show only the density of quantum dots, other data such as width, height, and volume can be deduced approximately and also can be estimated by naked eyes.

3.1 Optimizing growth temperature

Firstly, the growth temperature was changed from 460, 490, 510, and 530 to 550 ℃ with V/ III ratio fixed to 30, InGaAs thickness of 14ML. The measured AFM images of these samples are shown in Fig. 1, which are aligned with increased growth temperature. All of the images are 1μm × 1μm except the one grown at 460 ℃ (Fig. 1(a)).

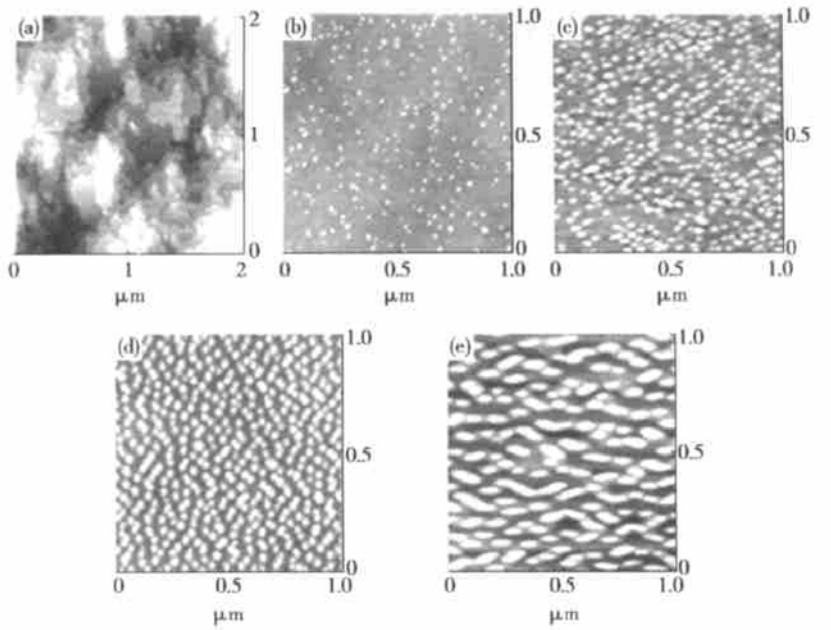

Fig. 1 AFM images of $In_{0.35}Ga_{0.65}As$/GaAs epilayer grown at the temperature of 460 ℃ (a), 490 ℃ (b), 510 ℃ (c), 530 ℃ (d), and 550 ℃ (e)

The measured density of quantum dots is shown in Fig. 2. Remarkable difference can also be observed through AFM images directly. When the growth temperature is as low as 460 ℃, there are no dots formed. Only steps can be observed in Fig. 1(a). At higher tempera-

The most desired growth condition of dots appears at growth temperature of around 530 ℃. For higher In concentration, the optimized temperature will decrease due to the increment of strain field plus temperature-induced atom mobility, which totally induced the SK growth of self-

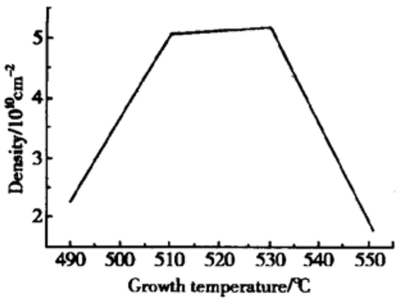

Fig. 2　Density versus growth temperature of QD

tures there are dots formation. The dot density reaches its maximum at temperature of 530 ℃, while dots size increases monotonously with the increment of temperature as can be seen from the images. The growth undergoes ripening of the dots at the temperature of 550 ℃ due to higher mobility of an atoms at this temperature.

assembled quantum dots formation. Snyder *et al*.[5] have concluded that the lowest growth temperature of quantum dot formation decreases with the increase of lattice mismatch strain. So the higher the In content in InGaAs/GaAs quantum dots system, the lower the optimized growth temperature is expected.

3.2　Optimizing amount of deposited materials

After optimized growth temperature was found, we grew several samples under this temperature with the only change of InGaAs deposition from 21, 17, 14, and 11 to 9ML. The measured AFM images of the epilayers grown under different epilayer thickness are shown in Fig. 3, which are ordered by the decrement of material thickness.

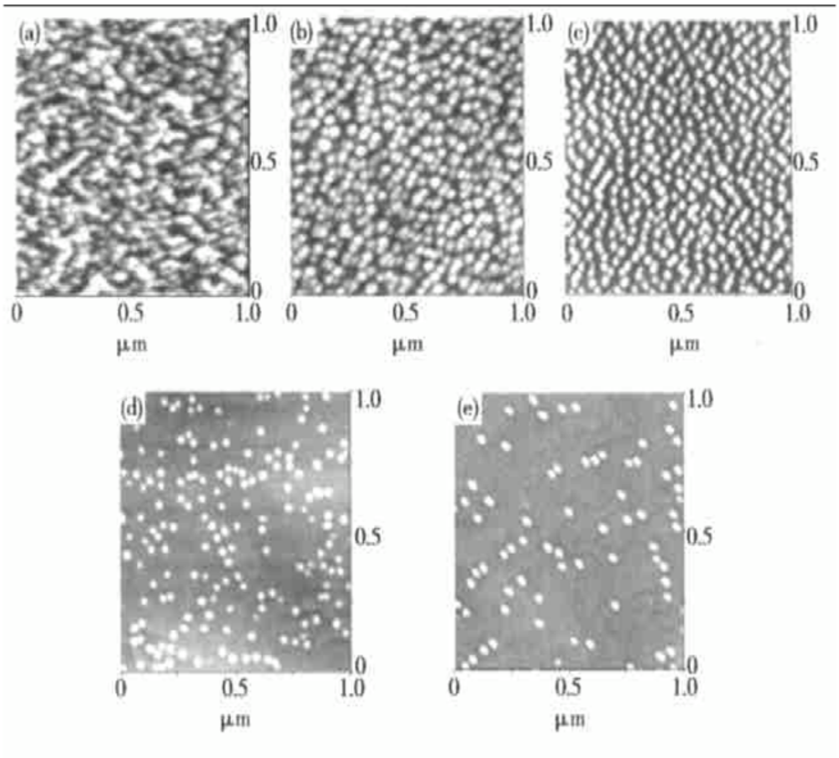

Fig. 3　AFM images of $In_{0.35}Ga_{0.65}As$ QDs with growth thickness of 21ML (a), 17ML (b), 14ML (c), 11ML (d), and 9ML (e)

The measured quantum dots density is shown in Fig. 4. We can see that for lower epilayer thickness the dots density decreased monotonously, thus we can control the dots density by depositing different amount of InGaAs. This rule had been revealed by many authors[1]. But we find that the dots distribution is not controllable and depends on the sub-layer status especially for low-density quantum dots with thinner InGaAs. With the increment of InGaAs deposited, the dots distribution gets much more ordered due to increased interaction of intra-layer quantum dots. So a certain amount of self-assembled materials is needed for high density and high uniformity of quantum dots growth.

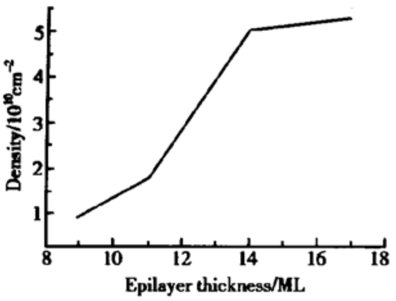

Fig. 4 Density versus InGaAs thickness of QD

It is not to say that the thicker the deposited material, the denser quantum dots will be. We can see that the sample with 21ML InGaAs deposition as shown in Fig. 3 (a). The dots overlap each other and some kind of undesired structures such as dis-locations have been formed. For our case, the critical thickness of InGaAs/GaAs quantum dots formation is around 10ML and in a range of about another 10ML quantum dots can also be formed with the partially release of lattice mismatch strain. However, with further increment of InGaAs, it comes into another region of strain relaxation to induce dislocations as shown by our overgrown sample. So the optimized thickness of QDs is similar to the growth temperature. They must be moderate and relate to the critical thickness of QDs formation, but must be lower than the critical thickness of dislocation formation. Here for $In_{0.35}Ga_{0.65}As$ QDs, the suitable thickness is around 14ML at temperature of 530℃.

3.3 Optimizing Ⅴ/Ⅲ ratio

Different Ⅴ/Ⅲ ratios have been applied to grow InGaAs/GaAs quantum structure also with Ⅴ/Ⅲ ratios of 7, 14, 21, 30, and 42, respectively at growth temperature of 530℃ and material thickness of 14ML. The measured AFM images are shown in Fig. 5, all in 1μm × 1μm scale.

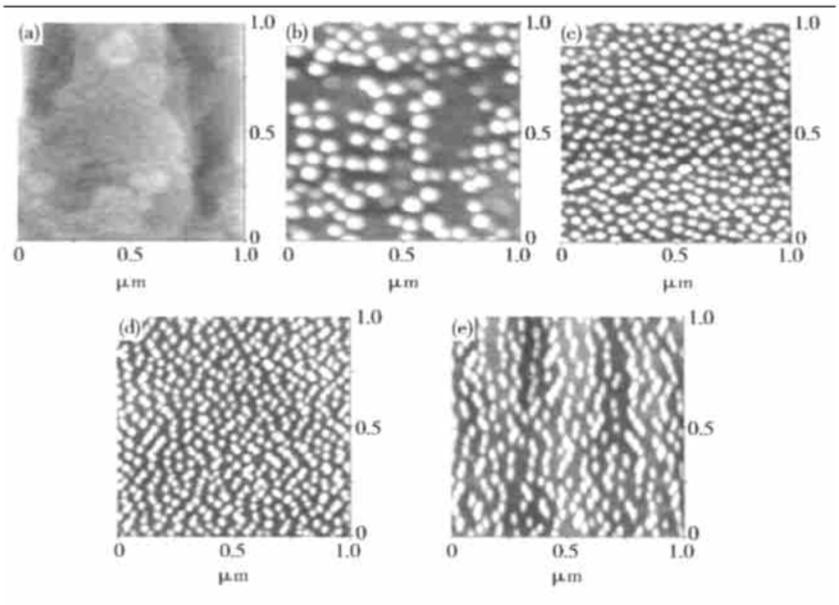

Fig. 5 AFM images of $In_{0.35}Ga_{0.65}As$ QDs with Ⅴ/Ⅲ ratio of 7 (a), 14 (b), 21 (c), 30 (d), and 42 (e)

The measured quantum dots densities are plotted in Fig. 6. Also under moderate condition the dots density reaches its maximum. Under too low Ⅴ/Ⅲ ratio there shows no dots formation while under too high Ⅴ/Ⅲ ratio the dots starts ripening into too big that with much lower density, which is also undesirable. We can explain this according to Ostwald ripening theory[6]. Decrease in surface energy favors the transition from ordering regime to ripening regime. In this regime, the increment of As partial pressure will cause the reconstruction change of the epilayer and a decrease of the surface energy[7]. All favor ripening of quantum dots. The samples of Ⅴ/Ⅲ changed

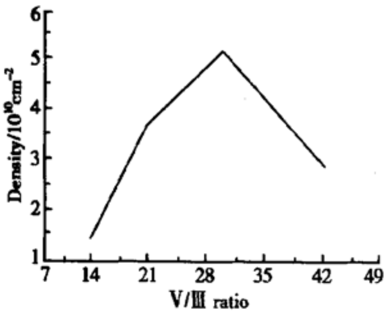

Fig. 6 Density versus V/III ratio of QD growth

from 30 to 42 show just this transition. On the other hand, at lower As pressure, In has stronger segregation to prevent the In, Ga, and As combination, thus it may cause quantum dots formation unfavorable. This agrees well with the results of Ledentsov *et al*. And we found that the transition V/III ratio is different from InGaAs quantum dots and InAs dots both using GaAs(001) substrate and solid source MBE. This may be due to the different lattice mismatchbetween InGaAs/GaAs and InAs/GaAs, which also affects the In and Ga interdiffusion. So when we grow InGaAs quantum dots of different In content, we must consider this effect.

3.4 Optimizing quantum dots using different Si doping profile and concentrations

In GaAs MBE processing, silicon always acts as n-type dopant. Thus the effect of silicon on quantum dots formation must be considered. Zhao *et al*.[8] also found that silicon can act as nucleus centers and induce smaller dots, thus increase the dots density. Growth conditions of quantum dots under different Si doping profiles are shown in Table 1, where we label the samples as A~G.

Table 1 Samples grown under different Si doping profiles

Sample No.	Doping start point/ML	Thickness after doping/ML	Dots density /10^{10}cm^{-2}
A	-	0	6.70
B	0	6	4.09
C	3	6	9.81
D	6	6	9.07
E	9	6	10.30
F	12	6	7.02
G	0	18	4.98

The measured AFM images are shown in Fig. 7 for samples A to G, respectively.

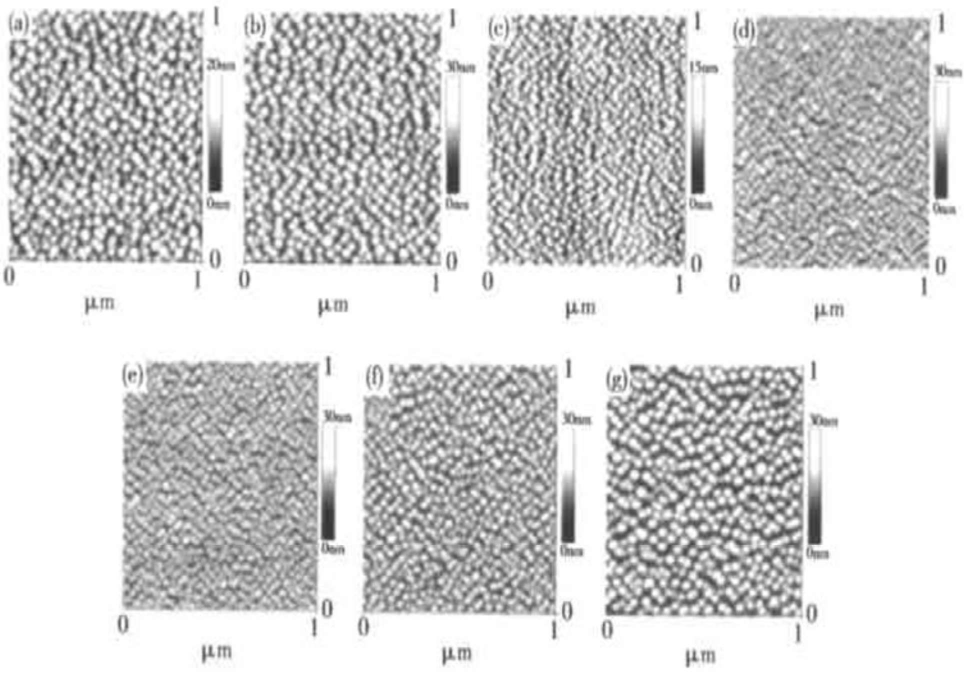

Fig. 7 AFM images of $In_{0.35}Ga_{0.65}As$ QDs (a) Sample A, (b) Sample B, (c) Sample C, (d) Sample D, (e) Sample E, (f) Sample F, and (g) Sample G

The measured quantum dots densities are plotted in Fig. 8. The $In_{0.35}Ga_{0.65}As$/GaAs critical thickness of quantum dots formation is found to be around 9 to 10 ML through our RHEED observation. This transition thickness is nearly same for silicon doped or undoped[9]. However, the dots density changed remarkably from $4.09\times10^{10}/cm^2$ to $10.3\times10^{10}/cm^2$. Those samples with highest density are doped around the critical transition thickness. Also our samples show no bi-mode distribution of quantum dots with different size from the AFM measurements. This shows that the silicon doping induces other mechanism in our case to significantly improve the dots density. Here we believe lattice-hardening effect is responsible. Silicon doping induces further pinning force to prevent the dots to grow into the bigger ones and it reaches its maximum at the transition point of layer to dot. Thus our case appears.

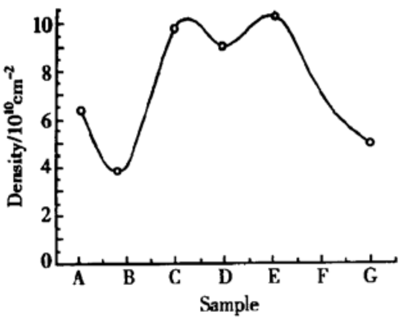

Fig. 8 Density versus silicon doping profiles of QD

4 Conclusion

We can find that in $In_{0.35}Ga_{0.65}As/GaAs(001)$ QDs formation, the best condition is around 14ML of $In_{0.35}Ga_{0.65}As$ deposited at temperature of about 530℃ with the V/III ratio of near 30. At very low V/III ratio and very low growth temperature, there will be no dots formed. Apparently it is true for very thin epilayers. On the opposite, much higher temperature and V/III ratio and thicker epilayermake the dots easier to be formed but will relax the strained quantum dots beyond some critical values. Proper silicon doping will increase the quantum dots density.

Compared with InAs/GaAs quantum dots, InGaAs/GaAs quantum dots of low In content has higher critical transition and optimizing temperature and different V/III ratio and thickness. Our silicon doping experiments also have effects on improving the density and uniformity of quantum dots, which will be helpful for the application of quantum dots in optoelectronics, such as quantum dot lasers and quantum dots infrared photodetectors.

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自组织量子点的优化生长

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摘要: 在不同生长条件下, 生长低组分 InGaAs/ GaAs 自组织量子点并且使用接触式 AFM 进行测量. 通过对生长条件的优化, 得到高密度、高均匀性的量子点 MBE 生长条件, 这对于自组织量子点在器件方面的应用, 比如量子点红外探测器和量子点激光器, 是非常重要的. 同时, 还与优化的 InAs/ GaAs 生长条件进行了比较.

关键词: InGaAs/ GaAs; 分子束外延; 原子力显微镜; 优化; 光电器件

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