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Journal of Crystal Growth 308 (2007) 406–411

JOURNAL OF CRYSTAL GROWTH

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The growth parameter influence on the crystal quality of InAsSb grown on GaAs by molecular beam epitaxy

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Received 9 July 2007; received in revised form 6 August 2007; accepted 18 August 2007
Communicated by H. Asahi
Available online 30 August 2007

Abstract

Serials $InAs_xSb_{1-x}$ samples grown on GaAs (0 0 1) substrates by solid source molecular beam epitaxy (MBE) have been investigated. The high-resolution X-ray diffraction (HRXRD) and atomic force microscope (AFM) results reveal that the quality and the surface morphology of $InAs_xSb_{1-x}$ strongly depend on the III/V ratio, growth temperature and the thickness of nucleation layer. When growth temperature is 400 °C, In:As:Sb is about 1:0.4:2, and the thickness of the nucleation layer is 30 nm, the sample has the smallest FWHM (797 arcsec), much better than the recent results [S. Nakamura, P. Jayavel, T. Kyama, Y. Hayakawa, J. Crystal Growth 300 (2007) 497; F. Gao, N. Chen, L. Liu, X.W. Zhang, J. Wu, Z. Yin, J. Crystal Growth 304 (2007) 472]. These results demonstrate that much better samples can be obtained by MBE. AFM surface particle analysis results show that surface morphology strongly associates with the surface particle size. Small particle size makes surface smooth and large particle size makes surface rough. Through optimizing the growth conditions, our samples have better crystal quality and smoother surface morphology. The sample which has the best crystal quality shows that the carrier mobility and density is $1.3\times10^4\,cm^2/V\,s$ and $1.3\times10^{17}\,cm^3$ at room temperature.

PACS: 68.55.−a; 68.37.Ps; 61.10.Nz

Keywords: A1. Atomic force microscopy; A1. X-ray diffraction; A3. Molecular beam epitaxy; B2. Semiconducting III–V materials

1. Introduction

Recently the growth of $InAs_xSb_{1-x}$ ternary alloy has received great interesting for their infrared devices applications [1–4]. $InAs_xSb_{1-x}$ ternary alloy as devices are operating at wavelengths in the 3–5 and 8–12 μm windows where the atmospheric absorption is minimum [5–8]. However, it is difficult to growth high-quality $InAs_xSb_{1-x}$ epilayer due to lack of proper substrate. Although many III–V substrates like GaAs, GaSb, InAs, InSb and InP can be selected for growing $InAs_xSb_{1-x}$, large lattice mismatch makes $InAs_xSb_{1-x}$ epilayers poor crystal quality. And GaSb, InAs and InSb substrates are expensive and poor quality compare to GaAs substrates although they have relative small lattice mismatch with $InAs_xSb_{1-x}$ epilayers. The heteroepitaxial growth of $InAs_xSb_{1-x}$ on GaAs substrates is attractive due to the large area, the availability of high-quality GaAs substrates, and more mature GaAs processing technology. However, since the lattice mismatch between $InAs_xSb_{1-x}$ and GaAs is very large ($7.2\%<\Delta a/a<14.6$), the growth of high-quality material is difficult [9]. The $InAs_xSb_{1-x}$ epilayers can be grown by different method, such as molecular beam epitaxy (MBE), MOCVD, LPE and HWE, We grow $InAs_xSb_{1-x}$ ($x<0.3$) samples on GaAs (0 0 1) substrates by MBE, the high-resolution X-ray diffraction (HRXRD) and atomic force microscope (AFM) indicates that we have obtained good crystal and surface morphology samples.

2. Experiments

All samples were grown on semi-insulating GaAs (0 0 1) substrates in a VG V80 MBE system with a conventional

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0022-0248/$ - see front matter
doi:10.1016/j.jcrysgro.2007.08.018

effusion antimony cell and valved arsenic cracker cell. The V group species from the cell were Sb_4 and As_2. The substrates were mounted on molybdenum blocks using indium. Prior to the growth, surface oxides was desorbed from the GaAs surface under As_2—rich flux protection at about 580 °C measured with a thermocouple calibrated by an IRCON infrared pyrometer. After 20 min growth of GaAs buffer, the surface of substrates become smooth, then the temperature was lowered to prepare for the growth of $InAs_xSb_{1-x}$. After a short interruption, undoped $InAs_xSb_{1-x}$ epilayer was grown on the smooth GaAs buffer under the different As/(Sb + As) beam equivalent pressure (BEP) ratio to acquire different As composition. All samples were grown for 1 h with the growth-speed 1 μm/h. Various conditions were adopted to grow samples. First, keep III/V ratios constant and change the growth temperature. Second, keep the temperature constant and change the III/V ratios. Third, different nucleation modes were adopted to grow 1-μm-thick $InAs_xSb_{1-x}$ epilayers (the temperature of nucleation is 300 °C). Forth, the influence on the crystal quality by using different thickness of nucleation layers was investigated. The difference of crystal quality influenced by lattice mismatch is neglectable in our samples and the growth conditions determine the crystal quality. Because, in our case, the largest x value of $InAs_xSb_{1-x}$ epilayers is less than 0.3 and the smallest lattice mismatch is larger than 9%. The (0 0 4) rocking curve is measured by Bede D1 system. Surface morphology was measured by the CSPM AFM system. The hall measurement was carried out by using conventional Van der Pauw method.

Table 1
The basic growth parameters of the first group experiments

Sample ID	III–V ratio (In:As:Sb)	Temperature (°C)	As composition	FWHM (arcsec)
1-1	1:0.4:4	480	0.15	4957
1-2	1:0.4:4	390	0.11	1405
1-3	1:0.4:4	420	0.11	3002

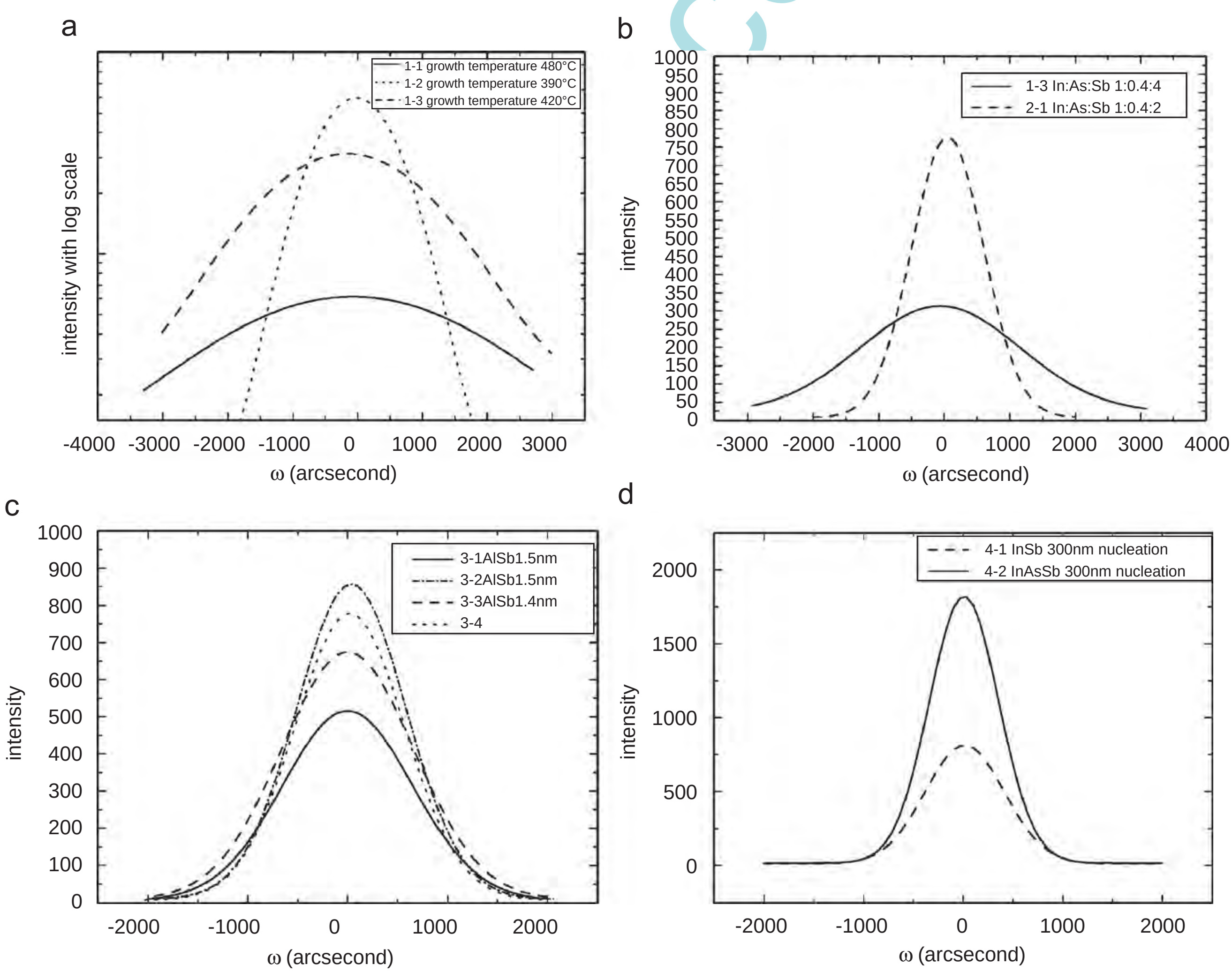

Fig. 1. The rocking curves of samples with (a) different growth temperature; (b) different flux ratios; (c) different nucleation; (d) InAsSb and InSb 30 nm nucleation layer.

3. Results and discussion

3.1. XRD analysis

Firstly, we discuss the experiments of the first group. Table 1 shows the basic growth parameters and Fig. 1(a) shows the corresponding HRXRD results. Fig. 1(a) shows that high substrate temperature will result in the increase of FWHM and Fig. 2(a) shows optical microscope image of the sample 1-1, the sample with high growth temperature has the bad surface morphology, the desorption of the five group elements due to high growth temperature is the main reason for this result. Fig. 2(b) shows the optical microscope image of sample 1-2, the surface morphology is much better than the sample 1-1. Under this flux ratio, the $InAs_xSb_{1-x}$ epilayer with growth temperature near 390 °C has relative good crystal quality. Table 2 shows the basic growth parameters of the second group experiments and Fig. 1(b) shows the corresponding HRXRD results. From above results, the III/V ratio has great influence on the FWHM. The increase of the FWHM attributes to that the large flux ratio can influence the indium atoms mobility on the surface. So, relative small III/V ratio can increase the crystal quality. In this case, the sample with the 1:0.4:2 In:As:Sb ratio is much better than the sample with the 1:0.4:4 In:As:Sb ratio. Table 3 shows the basic growth parameters of the third group experiments and Fig. 1(c) shows the corresponding HRXRD results. 1.5 nm AlSb was adopted as nucleation layer in samples 3-1 and 3-2. Fig. 1(c) shows that the crystal quality of sample 3-2 is better than sample 3-1. The growth temperature is believed to be the key point. The growth temperature near 400 °C is good for $InAs_xSb_{1-x}$ growth. Sample 3-3 has 1.4 nm InSb nucleation layer, but the nucleation layer does not apparent increase the crystal quality. Inversely, the sample 3-3 is worse than the sample 3-4 which was directly deposited on GaAs substrate. Although thin AlSb nucleation can effectively enhance the crystal quality in GaSb/GaAs system [10], in this case, due to large lattice mismatches, thin AlSb layer has no effects on $InAs_xSb_{1-x}$ epilayers. This group experiments shows that the growth temperature near 400 °C is good for growing $InAs_xSb_{1-x}$ and thin nucleation layer have no effect on epilayers. Table 4 shows the basic growth parameters of the forth group experiments and Fig. 1(d) shows the corresponding HRXRD results. This group experiments shows that no matter $InAs_xSb_{1-x}$ or InSb was adopted as the nucleation layer, the crystal quality can be improved by increasing the thickness of nucleation layer obviously. In this group experiment, the 30 nm $InAs_{0.02}Sb_{0.98}$ nucleation layer makes the FWHM 797 arcsec. The decrease of the FWHM attributes to that large lattice mismatch between GaAs and $InAs_xSb_{1-x}$ creates misfit strains and immiscibility problems. Since this mismatch initiates the $InAs_xSb_{1-x}$ growth on GaAs three dimensionally (3D), a smooth wetting layer formation at the early stage of the $InAs_xSb_{1-x}$ growth could prevent the defects near the InAsSb/GaAs interface and start the 2D growth. Low-temperature buffer layer can stop the dislocation and present the effective growth platform for the 2D growth [11].

3.2. AFM analysis

Table 5 and Fig. 3 show the AFM results about root mean square roughness and different particle size distribution ratios graphs. Samples 3-2 and 3-4 have the approximate particle size, although the sample 3-2 has the 1.5 nm AlSb nucleation layer. Fig. 3(a) shows the surface particle size distribution of sample 3-2. Particles whose size is less than 20 nm are about 30% and less than

Table 2
The basic growth parameters of the second group experiments

Sample ID	III–V ratio (In:As:Sb)	Temperature (°C)	As composition	FWHM (arcsec)
1-3	1:0.4:4	420	0.11	3002
2-1	1:0.4:2	420	0.12	1269

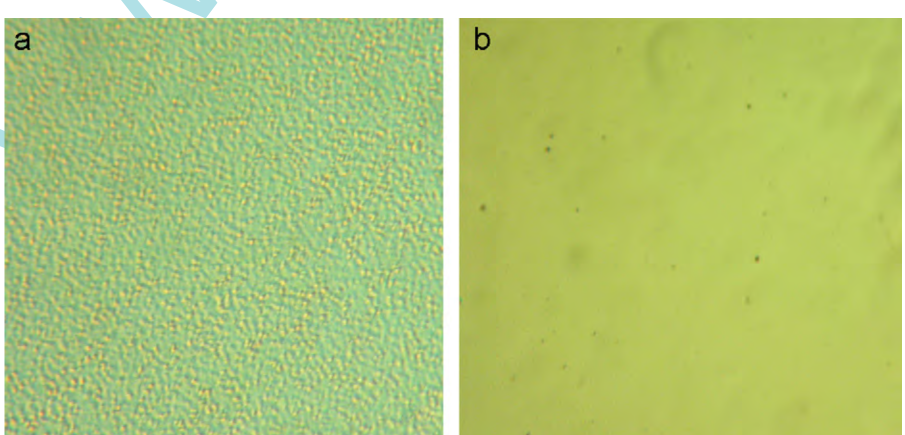

Fig. 2. Surface morphology of the first group samples by optical microscope: (a) the sample 1-1; (b) the sample 1-2.

Table 3
Shows the basic growth parameters of the third group experiments

Sample ID	III–V ratio (In:As:Sb)	Temperature (°C)	As composition	Nucleation mode	Nucleation thickness (nm)	FWHM (arcsec)
3-1	1:0.4:4	380	0.11	AlSb	1.5	1523
3-2	1:0.4:4	390	0.08	AlSb	1.5	1271
3-3	1:0.4:2	400	0.11	InSb	1.4	1550
3-4	1:0.4:2	400	0.08			1272

Table 4
Shows the basic growth parameters of the fourth group experiment

Sample ID	III–V ratio (In:As:Sb)	Temperature (°C)	As composition	Nucleation mode	Nucleation thickness (nm)	FWHM (arcsec)
4-1	1:0.4:4	420	0.22	InSb	30	914
4-2	1:0.4:2	400	0.17	InAsSb	30	797

Table 5
The RMS roughness, particle size distribution and FWHM

Sample ID	RMS (nm)	Average particle size (nm)	⩽50% particle size (nm)	⩽90% particle size (nm)	FWHM (arcsec)
3-2	1.99	91.58	60	210	1271
3-4	2.23	84.4	20	230	1272
4-2	4.51	161	140	360	797

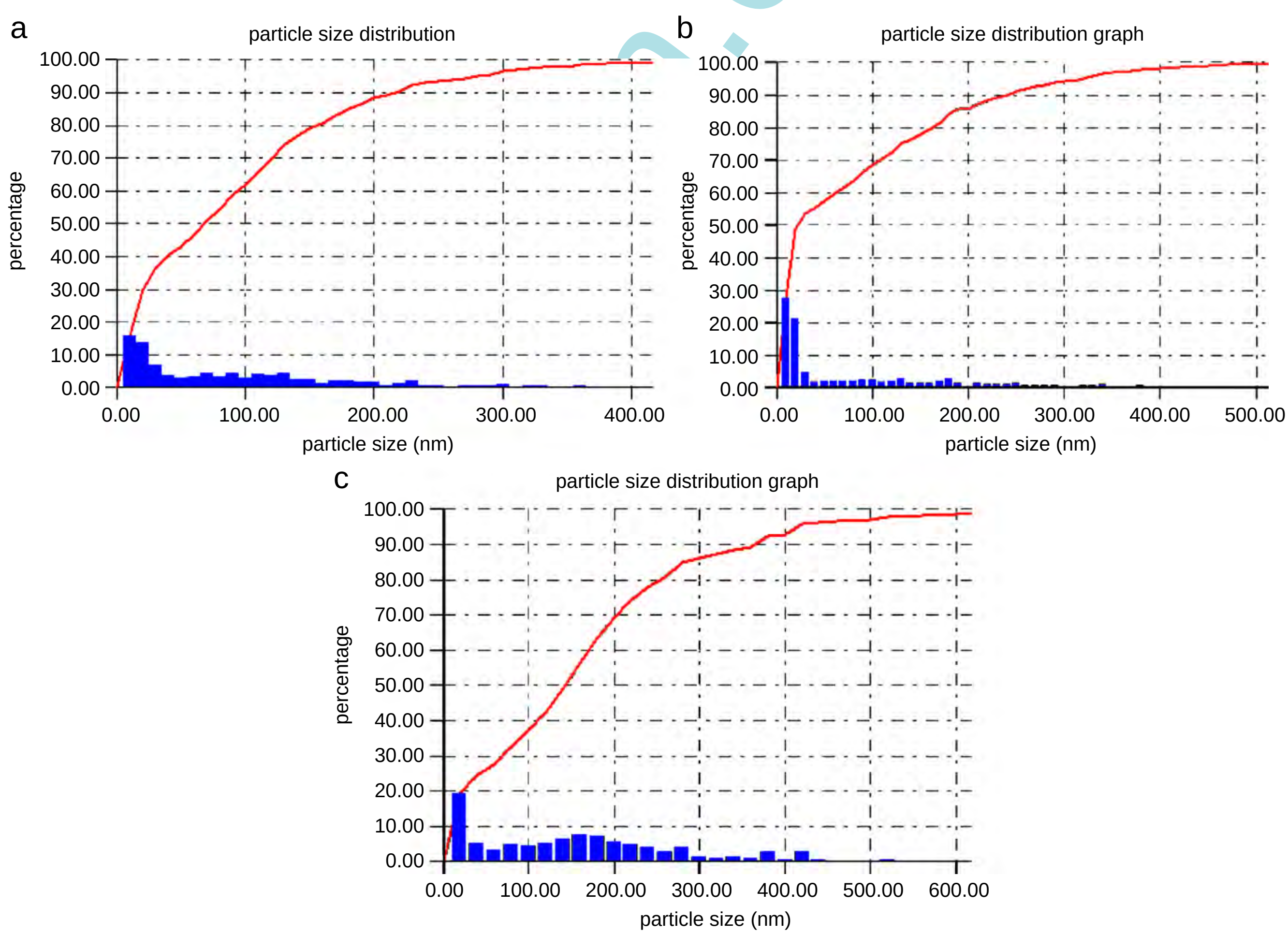

Fig. 3. Surface particle size distribution graph: (a) the sample 3-2 contains AlSb 1.5 nm nucleation layer; (b) the sample 3-4 directly grow on GaAs; (c) the sample 4-2 contains 30 nm InAsSb nucleation layer.

60 nm are about 50%. The particles whose size is larger than 60 nm are few. Fig. 3(b) shows that the sample 3-2 has the smaller average size than the sample 3-2, because the particles whose size is less than 20 nm are about 50 percentages. Fig. 3(c) shows that the sample 4-2 has larger particle size than above two samples. Its mainly particle size is about 100 nm. The average and mainly particle size of sample 3-2 are a little larger than the sample 3-1 which has no nucleation layer. The sample 4-2 has 30 nm $InAs_xSb_{1-x}$ nucleation layer, the average and mainly particle size are much larger than the samples 3-2 and 3-4. Fig. 4 shows the surface morphology of the samples 3-2, 3-4 and 4-2. The samples 3-2 and 3-4 have the smooth surface morphology and the sample 4-2 has the rough surface, although it has a better crystal quality. The AFM results indicate that the surface morphology is associated with surface particle size, small particle size relates to good surface morphology and large surface particle size relates to bad surface morphology. It is easy to understand these results, because large surface particle size causes large surface fluctuation. While small surface particle size makes surface fluctuation small and result in surface smooth. However, the key reason, we think, is the surface particle size influenced by mosaic structures in the crystal. The Table 5 shows that the sample 4-2 has the smallest FWHM but has the bad surface morphology. Surface particles come from the two stages: the nucleation stage and growth stage. The particles in the crystal determine the surface particles. In fact, the surface particles reflect the inner particles status. The surface particles small reflect the inner particle small; while the small particles make large number mosaic structures compare to the large particles for the same thickness samples. So, the samples with large particle size have small FWHM. However, the particle size related the thickness of nucleation layers, growth temperature and III/V ratios. In our case the 30 nm nucleation layers give large particle size, good crystal quality and bad surface morphology. We measured the carrier density and mobility of the samples. Fig. 5 shows X-ray rocking curve FWHM as a function of carrier mobility, the results show that carrier mobility and carrier density of the best sample (4-2) is $1.3\times10^4\,cm^2/V\,s$ and $1.3\times10^{17}cm^{-3}$ at room temperature.

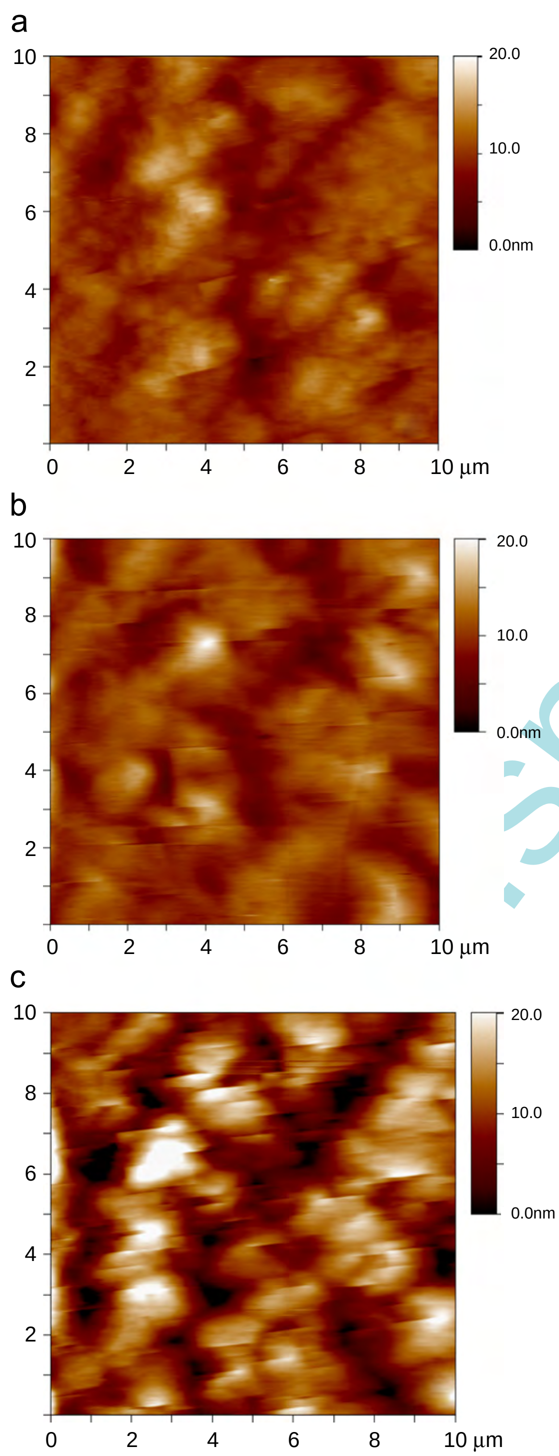

Fig. 4. AFM images of different buffer on GaAs. (a) the sample 3-2; (b) the sample 3-4; (c) the sample 4-2. Image size is $10\times10\,\mu m^2$ each and the bright and black height contrast is 20 nm.

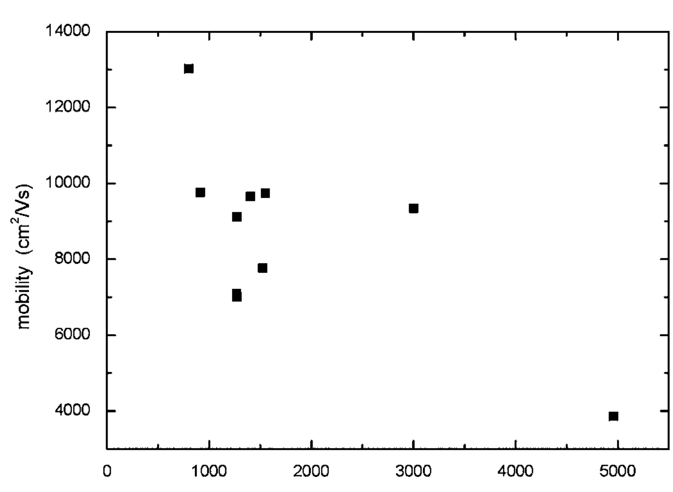

Fig. 5. X-ray rocking curve FWHM as a function of carrier mobility.

4. Conclusions

We did a serial group experiment to grow $InAs_xSb_{1-x}$ epilayers on GaAs substrates, the results demonstrate that the relative low III/V ratio, in our case 1:0.4:2, growth temperature 400°C and thicker nucleation layer increase the crystal quality. Through optimizing growth conditions, the sample with 797 arcsec FWHM was obtained. The results were much better than the samples grown by HWE and LPE. The AFM results indicate small surface particle size make good surface morphology, large particle size obtain bad surface morphology. In the same time, the surface particle size reflects the inner mosaic structures: small particle size related to large FWHM and large particle size related to small FWHM.

Acknowledgment

This work was supported by national Natural Science Foundation of China, No. 50572120.

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