Single Layer Growth of Strained Epitaxy at Low Temperature

Duan Ruifei, Wang Baoqiang, Zhu Zhanping and Zeng Yiping

(*Novel Materials Department, Institute of Semiconductors, The Chinese Academy of Sciences, Beijing* 100083, *China*)

Abstract: Contacting mode atomic force microscopy (AFM) is used to measure the $In_{0.35}Ga_{0.65}As/GaAs$ epilayer grown at low temperature (460℃). Unlike the normal layer-by-layer growth (FvdM mode) or self-organized islands growth (SK mode), samples grown under 460℃ are found to be large islands with atomic thick terraces. AFM measurements reveale near one monolayer high steps. This kind of growth is good between FvdM and SK growth modes and can be used to understand the evolution of strained epitaxy from FvdM to SK mode.

Key words: InGaAs/GaAs; molecular beam epitaxy; atomic force microscopy; epilayer; monolayer growth

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1 Introduction

For semiconductor devices using quantum dots as their active components, smaller size and higher density are almost the precondition of superior performance of these devices.

Low growth temperature had been used in InAs quantum dots to obtain small and with only one bound state in these zero dimensional semiconductor structures[1] to make these dots practical for super performance quantum dots infrared photodetectors[2,3]. Lee *et al*.[1] had grown InAs quantum dots at the growth temperature of 470℃ and successfully used the quantum dots in a bound to continuum infrared photodetectors. Ryzhii[2,3] had predicted a kind of quantum dot infrared transistors using quantum dots as its active region to have very super performance and to be able to work at very high temperature such as room temperature.

At the same time, higher density InAs quantum dots had also been observed using low temperature growth of (In, Ga) As quantum dots[4,5]. Suekane *et al*.[4] have shown that InAs quantum dots with the density as high as $4.6\times10^{11}cm^{-2}$ can be grown under the temperature of 420℃ of substrate. With the increment of growth temperature, the dot density decreased monotonously and lager dots were observed. Jonas *et al*.[5] had calculated the dependence of quantum dot density on growth temperature and found that almost exponential decrease of the dot density with the increment of growth temperature.

However, during the optimization of InGaAs quantum dots using lower growth temperature, we did not find QDs enhancement of the $In_{0.35}Ga_{0.65}As/GaAs$ (001) epilayer growth at temperature of 460℃. At such temperature $In_{0.35}Ga_{0.65}As$ was found unable to form dots but to show step by step growth of single monolayer of (In, Ga) As. So in this system with lower lattice mismatch (about 2%) than in InAs/GaAs (about 7%), higher growth temperature should be adapted to obtain higher QDs density.

Duan Ruifei male, was born in 1975, PhD candidate. He is engaged in InGaAs quantum dot and its applications for infrared photodetector.
Zeng Yiping male, was born in 1961, professor. He is engaged in MBE epitaxy of III-V semiconductor materials and the development of high-frequency and high-speed communicational and other microstructure devices.

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2 Experiment

Our sample was grown using EPI Gen II solid source MBE system. The growth temperature was calibrated through infrared bolometer, the accuracy of which was confirmed by the deoxidation temperature of GaAs substrate oxidation layer of 580℃. A 200nm GaAs buffer layer was first grown at the substrate temperature of 580℃. Then the temperature was dropped to 460℃ in As-rich condition. After the temperature got stable, a nominal 3.4nm (14ML) $In_{0.35}Ga_{0.65}As$ layer was deposited with the As pressure set at 10^{-3}Pa. Using this As pressure, we had grown $In_{0.35}Ga_{0.65}As$/GaAs quantum dots with high density and even uniformity at different growth temperatures. The islands formation was monitored in situ with RHEED (reflection high energy electron diffraction), which showed streaky patterns all over the growth periods. After the growth was over, the temperature was decreased as quickly as it could be and with only the As oven opened in order to keep the shape of the epilayer.

The sample was chipped into 5mm × 5mm squares out of the center and kept clean and dry and then measured with NanoScape IIIa AFM machine using contacting mode.

3 Results and discussion

From the observation of RHEED, we could not observe fully developed quantum dots or island formation due to its absence of dotty diffraction patterns. The patterns were kept line-shape though some kind of broken lines could be observed. Even after the period of the post growth, this was not changed. This can be confirmed by our result of AFM measurement. The measured epitaxy layer shapes of our sample are shown in Fig. 1.

Root-mean-square (RMS) surface roughness had been used comprehensively in the evaluation of the roughness of materials[6]. We calculated the RMS surface roughness of our sample of Fig. 1 (b) and found a value of 0.2786nm, which is much smaller than 2.0115nm, the RMS surface roughness of sample grown under same conditions except the growth temperature of 530℃. Both measurements were in the range of 2μm × 2μm and analyzed with same software in same conditions. This flat property caused the unchanged RHEED pattern.

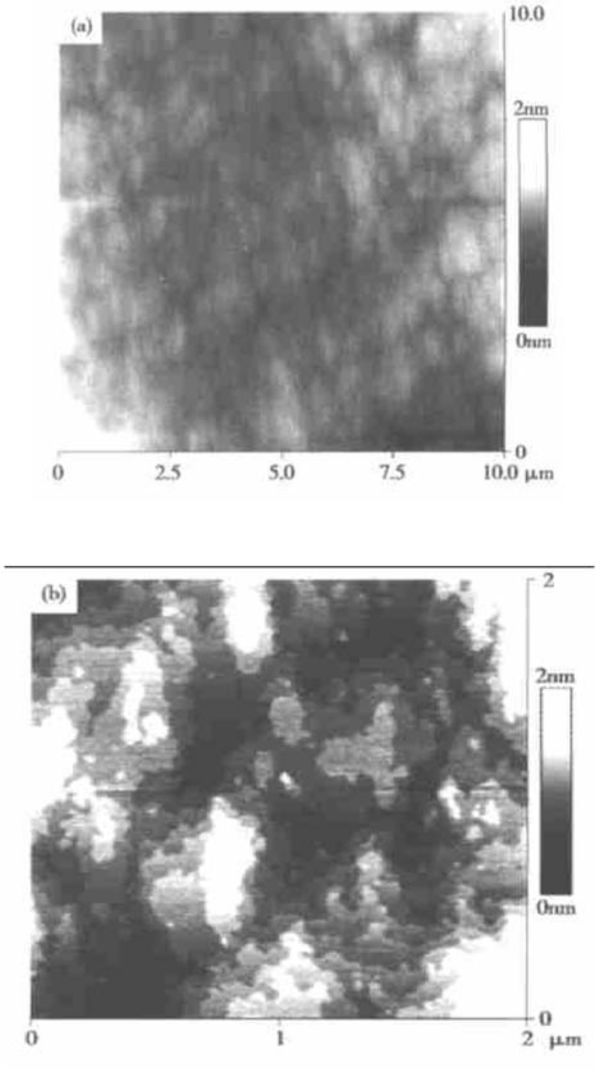

Fig. 1 10μm × 10μm (a) and 2μm × 2μm (b) AFM images of single ML grown epilayer

From those scan lines of Fig. 1 (b), we selected one of them and drew it in Fig. 2. An interesting phenomenon was observed. There exist several step-like structures when we scan along x-axis and the heights of these steps are almost the same. From these well-defined steps, we found that the height of the steps is about 0.28nm. This value is close to the calculated monolayer thickness of $In_{0.35}Ga_{0.65}As$, which is about 0.29nm. The difference may be caused by the transverse resolution of AFM measurement and the systematic error due to fluctuation. To AFM measurement, the vertical resolution (perpendicular to the tip) is about 0.01nm, so our result is good within the extent of error.

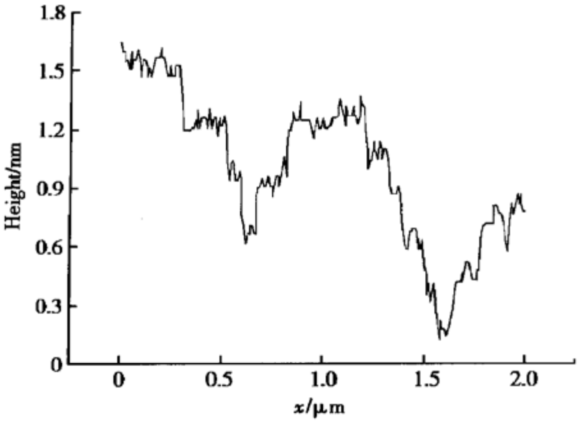

Fig. 2 One line scans of the steps of our sample along x-axis The height of the steps is about 0.28nm.

There exist three different growth modes in strained epitaxy: Frank-van-der-Merwe (FvdM), Stranski-Krastanov (SK), and Volmer-Weber (VW) mode, which represent layer-by-layer growth, layer plus islands growth, and islands growth respectively. FvdM and SK are commonly used in III-V semiconductor material epitaxy by MBE or MOCVD. Due to the growth kinetics of FvdM or SK growth modes, there exists a critical thickness, at which FvdM growth changes to SK one. The thickness is related to two factors: one is the lattice mismatch strain; the other is growth temperature. Growth temperature mainly provides migration power for the adatoms. And the lattice mismatch is the driving force for a cause of the surface instability, which fluctuates the flat surface into a wavy one. At higher temperature, QD had been observed in InGaAs/GaAs systems with low indium content but with higher growth temperature. So the steps of our sample are caused by the combination of the smaller lattice mismatch and the lack of migration driving force caused by the low growth temperature. The lattice mismatch caused the wavy pattern on the epilayer surface and the low growth temperature had lower power to make the adatoms to overcome the barrier, which prevents them from moving downward or upward to form the normal quantum dots structure. Through our experimental results, we can find that there exists a mosophase between layer and island of lattice mismatched InGaAs/GaAs system. For the very promising quantum dots formation, we find that both lattice mismatch and the migration driving force are very important factors for quantum dot formation. So the consideration of critical thickness of SK growth without concerning the temperature dependence is not proper. The two factors together enables the formation of quantum dots, thus determined the critical thickness. Due to the lack of growth temperature induced atomic driving force we can not obtain quantum dots in our sample but macroscopic mounds with monolayer steps. And lack of lattice mismatch will surely fail to produce self-assembled quantum dots. Those who wish to have good quality QDs must consider these two factors at the same time.

4 Conclusion

$In_{0.35}Ga_{0.65}As$ on GaAs (001) substrate at very low growth temperature of 460℃ had been researched through contacting mode AFM. We found that the suitable low temperature for higher density InAs/GaAs quantum dots growth does not work to low In content InGaAs/GaAs quantum dot systems. Unlike the usually layer-by-layer growth (FvdM mode) or self-organized islands growth (SK mode), sample grown under 460℃ were found to be macroscopic mounds with terrace-like patterns. AFM measurements revealed near one monolayer high steps of the terraces. This kind of growth is good between FvdM and SK growth mode and reported only on lattice mismatched GaAs on vicinal GaAs substrate. Our results revealed a kind of mosophase between layer and island growth thus can be used to understand the evolution of strained epitaxy from FvdM to SK mode.

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低温下应变外延层的单层生长

段瑞飞　王宝强　朱占平　曾一平

(中国科学院半导体研究所 新材料部, 北京　100083)

摘要: 用接触式原子力显微镜来观察460℃低温下生长的$In_{0.35}Ga_{0.65}As/GaAs$外延层形貌. 实验发现, 这种460℃低温生长材料的失配外延层既不是层状的FvdM生长模式也不是岛状的SK自组织生长模式, 而是由原子单层构成的梯田状大岛. 原子力显微镜测试表明台阶的厚度为0.28nm, 约为一个原子单层, 这种介于层状和岛状生长之间的模式有助于了解失配异质外延的生长过程.

关键词: InGaAs/GaAs; 分子束外延; 原子力显微镜; 外延层; 单层生长

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段瑞飞　男, 1975年出生, 博士研究生, 从事量子点及其红外探测器的研究工作.

曾一平　男, 1961年出生, 研究员, 博士生导师, 目前主要研究方向为III-V族化合物半导体微结构材料及分子束外延技术.

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