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Atomic hydrogen induced step bunching and fabrication of quantum wire arrays on GaAs (311)A substrate by molecular beam epitaxy*

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Atomic hydrogen assisted molecular beam epitaxy (MBE) is a novel type of epitaxial growth of nanostructures. The GaAs (311)A surface naturally forms one-dimensional step arrays by step bunching along the direction of $\langle -233 \rangle$ and the space period is around 40nm. The step arrays extend over several μm without displacement. The InGaAs quantum wire arrays are grown on the step arrays as the basis. Our results may prompt further development of more uniform quantum wire and quantum dot arrays.

Keywords: molecular beam epitaxy (MBE) step bunching, InGaAs, quantum wire
PACC: 6822, 8115C, 6120

1. Introduction

Surface morphology of the grown surface layer can be strongly modified by atomic hydrogen assisted molecular beam epitaxy (MBE) on GaAs (311)A substrates. Atomic hydrogen has the effect of removing oxygen and carbon from the substrate.[1] Under optimized growth conditions, atomic hydrogen promotes the selective growth on patterned and masked substrates by active Ga and As.[2] GaAs (311)A substrates only form unstable micro-step bunches in conventional MBE. When atomic hydrogen is supplied during MBE on high-index substrates, natural self-faceting is promoted by step bunching along a specific direction.[3] To fabricate quantum structures of good growth quality and uniformity, many methods have been tried,[4,5] but they are subtle or limited to the scale of 10–100nm. Self-organized step bunch structures formed by atomic hydrogen assisted MBE avoid these shortcomings. However, this method is novel, so the growth parameters are difficult to adjust to ensure growth quality. More in depth research is needed to understand the mechanism of the effect of atomic hydrogen during MBE growth.

In this paper, we present the appropriate growth parameter to form macro regular step bunches by atomic hydrogen assisted MBE. The addition of atomic hydrogen leads to stable step arrays with a lateral periodicity of 40nm and 2–3nm height along the direction $\langle -233 \rangle$. The step-like structures extend over several μm without displacement. Above the step-like structures, we succeeded in developing sites of orderly arranged quantum wire and dot arrays. Our experimental results give useful information for better understanding of the selective growth of quantum dot structures with atomic hydrogen assisted MBE.

2. Experiment

The MBE growth system used in our experiments is VG V80H MK II. For atomic hydrogen assisted MBE growth on GaAs (311)A substrate, the substrate was prepared by, etching and cleaning in the H_2SO_4:H_2O_2:H_2O (1:8:40) preferential, etching solution for 5 min. Then it was flushed by DI water,

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and was blown by pure nitrogen gas. The substrate was then glued to a molybdenum block with indium. The growth rate of GaAs was $0.3\mu m \cdot h^{-1}$ at a substrate temperature of 620°C with the group V-III flux ratio of 10. Atomic hydrogen was supplied through a cracker cell using a W filament heated to 1800°C. During 5 min irradiation of atomic hydrogen, the native oxidation on the GaAs surface was removed at a low substrate temperature of 300°C. This procedure is comparable to other sources reported in Ref.[1]. The low substrate temperature was confirmed by monitoring the reflection high-energy electron diffraction (RHEED) patterns. During the whole growth process, the rotation speed of substrate was kept at 20rol/min and the background pressure in the MBE chamber was about 5×10^{-5}Pa. The surface morphology was measured by atomic force microscopy (AFM). The AFM test was carried out in the contact mode in the atmospheric environment.

3. Step bunching on GaAs (311)A substrate

Figure 1 shows the AFM view of step bunching by atomic hydrogen assisted MBE compared with normal morphology of surface prepared by conventional MBE. The growth structures are both 100nm thick GaAs layer grown at a substrate temperature of 620°C on GaAs (311)A substrate. In conventional MBE, the surface morphology only shows fine steps about one monolayer high, extending over several 10nm. The asymmetric morphology structure reflects that the diffusion length of Ga atoms is larger along $\langle -233 \rangle$ than along $\langle 01-1 \rangle$, which is determined by the surface atom distribution. Compared with conventional MBE method, the surface morphology shows distinct quasi-periodic step bunch arrays along $\langle -233 \rangle$ in atomic hydrogen assisted MBE. The lateral periodicity of the step arrays is around 40nm, and the height is around 2–3nm. The step bunches extend over several μm with few crossing places. Thus they are very good templates for the self-organized formation of wire-like or dot-like nano devices.[6,7]

Our view about this step bunching phenomenon is that atomic hydrogen changes the bond energy of Ga atoms on the substrate surface. GaAs (311)A surface has natural fine steps, the surface morphology is reformed through the migration of Ga atoms on the surface. Some authors have studied other atoms' migration on surface.[8,9] Surface bond energy of Ga atoms is reduced with the introduction of atomic hydrogen, and then, according to the solid-on-solid (SOS) model,[10,11] the hopping rate of Ga atoms, R, is increased following the expression

$$R = R_0 \exp^{-E/k_B T},$$

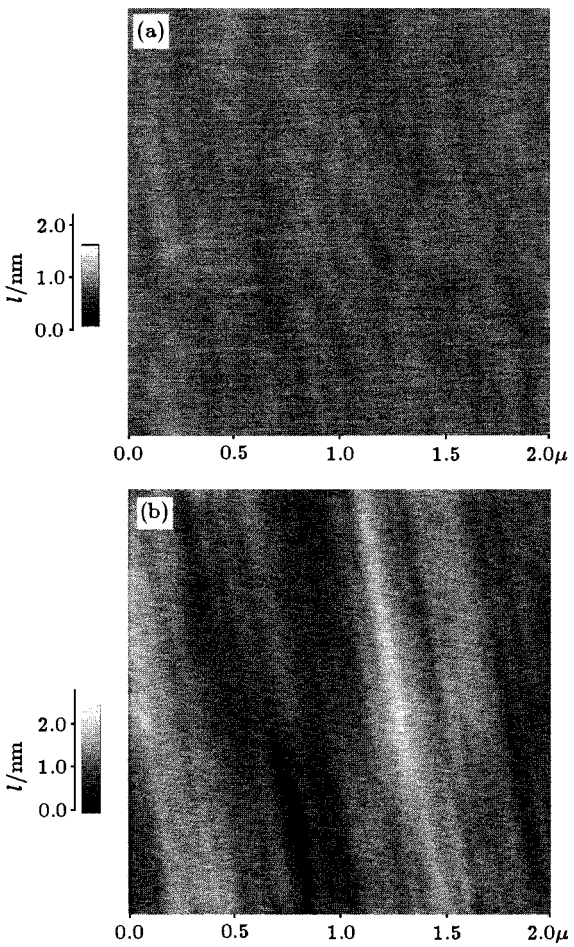


Fig.1. (a) AFM top view of 100nm thick GaAs layer grown on (311)A substrate at 620°C by conventional MBE; (b) AFM top view of 100nm thick GaAs layer grown on (311)A substrate at 620°C by atomic hydrogen assisted MBE.

where R_0 is a characteristic vibration frequency of atoms, E is the activation energy which is determined by the neighbour atoms environment, k_B is the Boltzmann's constant, and T is the substrate temperature. So, the migration of Ga atoms is enhanced. Ga atoms migrate more freely in the presence of atomic hydrogen than in conventional MBE. The fine step bunches become larger and higher through the migration of Ga atoms between the step bunches.

The whole reforming process of step bunching is shown in Fig.2. Initially, there are fine steps on the substrate surface, and with atoms supplied, some atoms form two-dimensional nucleus on the fine step

terrace rather than attach to the step edges. During growth, some atoms move in the descending direction (from upper steps to lower steps), and eventually the two-dimensional nuclei merge with the ascending steps. Thus, new growth facet forms and fine step bunches merge with each other to wider and higher macro step bunches.[12]

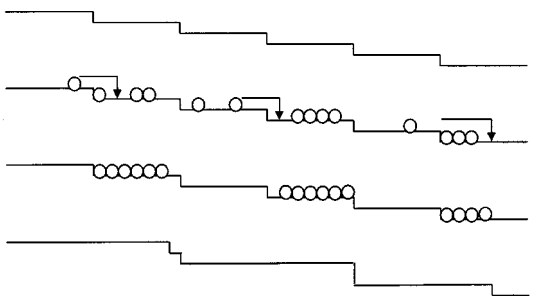


Fig.2. Reform process of step bunching.

It is noteworthy that the SOS model is a simplified model, and the mechanism of growth in atomic hydrogen assisted MBE is complex. In real experiments, there may be still other factors helping to develop the step bunches higher and wider.

4. Self-organized formation of quantum wires arrays

On the basis of step bunching, we grew InGaAs quantum wires on the step-like structures. Figure 3 shows AFM image of quantum wire arrays on the step bunches. The GaAs (311)A substrate was deoxidized with atomic hydrogen irradiation at a low temperature of 300°C and then deposited with 100nm GaAs to form macro step bunches at substrate temperature of 620°C. It was followed by depositing 3.5nm $In_{0.2}Ga_{0.8}As$ with As growth rate of $0.1\mu m{\cdot}h^{-1}$ and GaAs growth rate of $0.4\mu m{\cdot}h^{-1}$ at substrate temperature of 540°C. Self-organized quantum wire arrays along $\langle -233 \rangle$ are formed. The height of quantum wires is about 8nm. At some places of the quantum wire arrays, there formed sporadic quantum dots. It shows that there are some "stressors" for quantum dots. This image shows that there is a quantum wire site on top of each step bunch, since their quasi-periodicity, 40nm, agrees with the quasi-periodicity of GaAs step bunches below. It indicates that the step bunching morphology below has influenced the site distribution of InGaAs quantum wires and dots above.

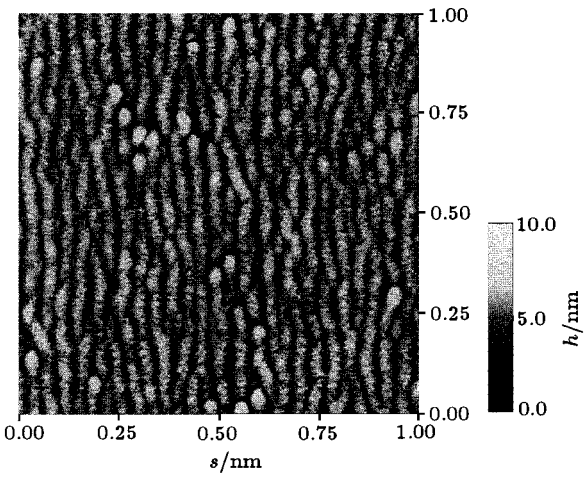


Fig.3. InGaAs quantum wires (and dots) orderly arranged on step bunches by atomic hydrogen assisted MBE.

These quantum wire arrays are formed by self-organization, and the growth quality is better than those obtained by depositing quantum wires or dots on the, etched lithographic terraces on the surface of substrates.[13] It presents a novel way to manufacture two-dimensional quantum devices.

5. Conclusion

We presented a novel method to fabricate dense wire-like nanostructure arrays by depositing InGaAs on step bunching structures of GaAs (311)A substrates. The atomic hydrogen promotes the formation of macro step arrays along $\langle -233 \rangle$ with a lateral periodicity of about 40nm and height of about 2–3nm. Step bunches extend over several μm without displacement. The sites distribution of InGaAs quantum wires deposited above the step bunches is orderly controlled.

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