Development of Cross-hatch Pattern on InGaAs/GaAs Virtual Substrate

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ABSTRACT

$In_{0.15}Ga_{0.85}As$ strained layer on GaAs (001) substrate is grown by molecular beam epitaxy (MBE). An approach for understanding the misfit dislocations aligned along two orthogonal <110>directions at the interface of InGaAs/GaAs virtual substrate is developed. Well-defined cross-hatch morphology on the surface of the virtual substrate due to the presence of networks of misfit dislocations has been revealed by means of atomic force microscopy (AFM). The origin of the morphology is confirmed by cross-sectional transmission electron microscopy (TEM). Fast Fourier transform (FFT) analysis is performed in order to deduce the average lateral periodicity of the misfit dislocations. From the FFT measurement, the average lateral periodicity of the misfit dislocations along [110] is 890 nm in the perpendicular [1-10] direction which is in a good agreement with the average distance value between the two signal peaks of line profile from AFM image.

Keywords: misfit dislocation, cross-hatch pattern, molecular-beam epitaxy (MBE)

1. INTRODUCTION

The growth of self-assembled quantum dots (SAQDs) formed in Stranski-Krastanov (SK) growth mode is useful for electronic devices because of their defects-free characteristics and uniform size. Although the benefits of SAQDs are obvious for some applications, their random distributions result in poor qualities of electronic and optical devices. Therefore, ordered QDs are necessary to overcome these problems and also to achieve better QD-based devices such as single transistor and quantum dot cellular automata. There are various methods which can be used to form laterally- and vertically-ordered QDs; for examples, the use of high-index substrate [1], substrate with insulated mask or anodic porous alumina mask [2,3], multi-layered vertical stacking grown at elevated temperature [4,5] and multi-layered high-stepped vicinal substrate or strained layer growth on patterned substrate [6-10]. At present, no one best technique has been claimed to be most suitable for ordered-QDs growth but the development of cross-hatch morphology is a powerful technique [11].

Most methods for ordering of QDs are generally obtained from strained semiconductor heterostructures. Epitaxial growth of heterostructure is accompanied by strain in the epitaxial layer that results from the difference in lattice parameters between the substrate and the epilayer. For large lattice-mismatched system, 3-dimensional (3D) self-assembled islands growth mode can be formed after the epilayer thickness is over a critical thickness (h_c). For small ($< 2\%$) lattice-mismatched system, the growth occurs layer-by-layer via a step flow mechanism, after which, 60° misfit dislocations (MDs) are accompanied by threading dislocations which propagate into the epitaxial layer [12]. A characteristic undulating surface morphology due to the presence of network of dislocations is known as cross hatch. The characteristic surface morphology which is usually observed in InGaAs/GaAs systems exhibit elongated ridges and valleys along <110>directions [13,14]. In this paper, we report on the growth of $In_{0.15}Ga_{0.85}As$ strained layers on GaAs (001) substrates. Surface morphology of epitaxial layer is studied by AFM and TEM techniques. Specially, we reveal and propose a model for the evolution of cross-hatch pattern onto the InGaAs/GaAs virtual substrate.

2. EXPERIMENTAL DETAILS

All samples are grown on semi-insulating (001) GaAs wafers by solid-source RIBER 32P molecular beam epitaxial system. In order to control the surface reconstruction in real time, in situ reflection high-energy electron diffraction (RHEED) is used throughout the growth. After oxide desorption of the substrate, a buffer layer of GaAs with a thickness of 300 nm is grown to flatten the surface with a growth rate of 0.34 ML/s at 615 °C for sample A shown in Fig.1(a) and at 600 °C for sample B shown in Fig.1(b). The substrate temperature is then reduced to 500 °C to grow 50 nm of $In_{0.15}Ga_{0.85}As$. After that, a 30-second growth interruption is introduced and the substrate temperature is rapidly ramped down to 100 °C

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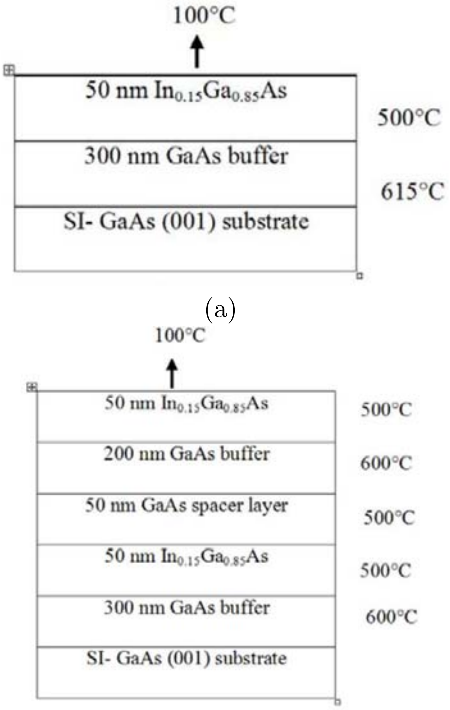
to maintain the surface morphology of the sample. For the investigation of dislocation propagation, the structure grown in the previous stage is extended by the growth of 50 nm thick GaAs spacer layer at 500 °C and followed by growth of 200 nm of GaAs layer at 600 °C. Finally, 50 nm of $In_{0.15}Ga_{0.85}As$ layer is grown at 500 °C. During growth, the growth rate of $In_{0.15}Ga_{0.85}As$ is 0.4 ML/s and the beam equivalent pressure of As_4 is fixed at 6.110^{-6} Torr. Schematic diagrams of grown structures for this experiment are shown in Fig.1.



(a)

(b)

Fig.1: *Schematic diagrams of the grown structures for the studies of (a) sample A, cross-hatch morphology and (b) sample B, dislocation propagation.*

3. RESULTS AND DISCUSSION

In order to confirm the structure of the sample, the surface morphology of the grown sample is observed under an atomic-force microscope (AFM). The AFM image of the surface of the sample shown in Fig.1(a) is shown in Fig.2. A well-defined cross-hatch pattern can be observed. The lattice mismatch between $In_{0.15}Ga_{0.85}As$ and GaAs layers is 1.07%. Since the lattice mismatch is less than $< 2\%$, the most probable growth mode is 2D layer-by-layer. For 15% In composition, the critical thickness is 10 nm according to Matthews and Blakeslee's model [15]. Since the strained-layer thickness for this sample is considerably larger than the hc value for MDs (i.e. $5h_c$), the structure is partially relaxed by the formation of MDs at the interface. These MDs can thread to the surface at 60° angle which results in a cross-hatch appearance when viewed from the top.

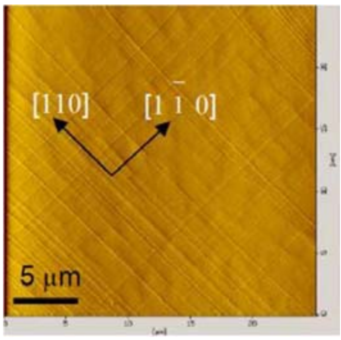


Fig.2: *AFM image of the surface of $In_{0.15}Ga_{0.85}As$ layer on GaAs (001) substrate.*

The result is in a good agreement with existing models in which cross-hatch morphology is derived from MD generation and glide processes [16,17]. But, this result is in contrast to other alternative models which suggest that the cross-hatch pattern results from enhanced growth strained relaxed regions due to lateral mass transport by surface diffusion [18], or from composition fluctuations in the layer of ternary compounds [19].

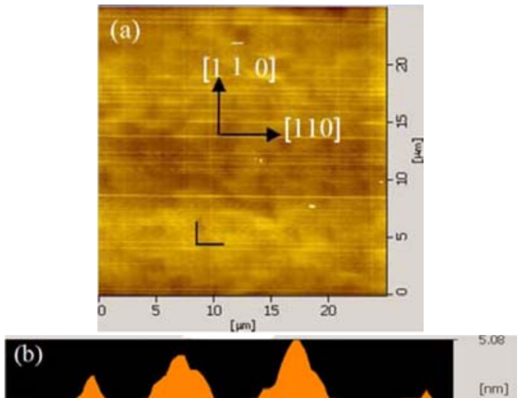


Fig.3: *Different orientation of AFM image of InGaAs/GaAs. Line profiles of InGaAs layer on GaAs (001) substrate along (b) [110] and (c) [1-10] directions.*

The line profiles of the $In_{0.15}Ga_{0.85}As$ taken along the <110>directions indicated by the line marks shown in Fig.3(a) is shown in Fig. 3(b) and (c). The peak-to-valley amplitude of surface undulations along the [110] direction is 1.07 nm while those along the [1-10] direction is 1.17 nm. These two difference values can be explained by a relation between ridges and dislocation which depends on unequal stress on two different sides of the dislocation, which in turn depend on oblique intersection of Burger vectors for 60°-type dislocation [20]. The root-mean-square (rms) roughness of this sample is 0.627 nm.

A lateral periodicity of MDs from AFM result is detected by fast Fourier transform (FFT) analysis. Therefore, the period (distance) T of signal can be calculated by the relation between period and frequency (f):

$$T(\mu m) = \frac{1}{f}$$

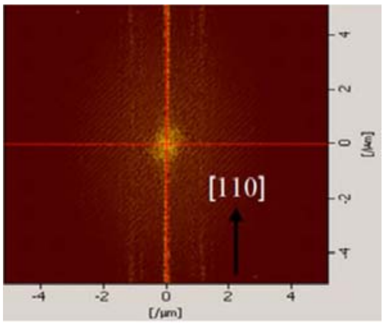


Fig.4: *FFT analysis of* $25\times25\ \mu m^2\ In_{0.15}Ga_{0.85}As$ *layer on GaAs substrate along [110] direction.*

Fig.4 shows the FFT result obtained from AFM image of Fig.3(a). The average frequency of the signal between the original point and the first harmonic signal (fundamental frequency) is $1.123\mu m^{-1}$ which is deduced from FFT analysis. Therefore, the period becomes 890 nm according to the formula shown above. This means that the average lateral periodicity of MDs oriented along [110] is 890 nm in the perpendicular [1-10] direction, which is the evidence of the results that we are already shown from the line profile analysis in Fig.3(b).

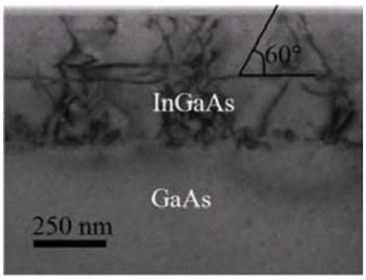


Fig.5: *Cross-sectional TEM image of InGaAs/GaAs layer.*

In order to confirm the formation of cross-hatch pattern from the MDs, further investigation is applied by a cross-sectional transmission electron microscopy (TEM). Fig.5 is the TEM image of the structure shown in Fig.1(b). A network of dislocations across the InGaAs/GaAs interface due to the misfit strain of heteroepitaxial system can be clearly seen in this figure. Most of the misfit dislocations are found to be mixed dislocations that glide on {111} which propagated along<110>directions as shown in Fig. 5. This result is in consistent with the result of a surface morphology study which used in AFM. Therefore, it is clear that cross-hatch patterns develop after the misfit dislocations are generated.

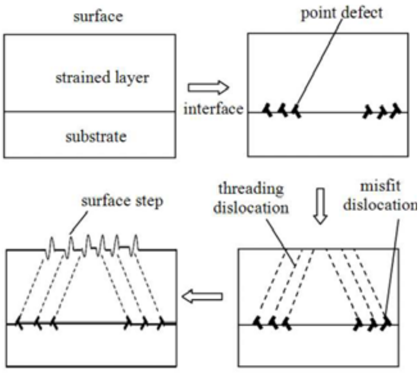


Fig.6: *Schematic diagram of the development of cross-hatch morphology.*

A model describing the evolution of cross hatch is shown in Fig.6. When the deposition thickness of the strained layer is comparable to h_c, small amount of defects called point defects nucleated at the hetero interface. The misfit strain energy in the layers increases with increasing the epilayer thickness. The energy is released by the gliding of MDs, which thread to the surface at 60° angle until they are annihilated when met with other MDs, otherwise they thread to the surface and appear as small steps which register on the AFM image as cross-hatch pattern.

4. CONCLUSION

$In_{0.15}Ga_{0.85}As$ strained layer is grown on GaAs (001) substrate. The structure of misfit dislocations at the interface and the threading dislocations that are terminated at the surface which appears as cross-hatch morphology are studied by AFM and TEM. The results indicate that well-defined cross-hatch pattern is the consequence of threading dislocations formed by the gliding (at 60°) of misfit dislocations. MDs with the average spacing of 890 nm are detected by FFT analysis which is consistent with the lateral periodicity of the MDs in the virtual substrate determined by AFM.

5. ACKNOWLEDGEMENT

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