Selective self-organization of InAs islands on InGaAs/GaAs buffer layers

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Abstract

InAs islands were grown on two kinds of InGaAs/GaAs buffer layers by molecular beam epitaxy, which were strained InGaAs buffer layer grown on the GaAs(001) substrate and the mesa stripe of the InGaAs/GaAs multi-quantum-wells (MQWs) buffer layer. InAs dot structures were partially formed on the InGaAs surface and aligned selectively along the <110> direction. It suggests that the distribution of the residual strain exists on the InGaAs surface, and, as a result, InAs dots are formed only on the relaxed InGaAs area, but not on the strained area. The selectivity of InAs dots depended on the thickness of the InGaAs buffer layer. While, in case of the mesa-stripe MQWs buffer layer, InAs islands were observed only on InGaAs QWs of the side wall, but not on GaAs barrier layers. It was found that indium adatoms on the GaAs surface migrate to the InGaAs QW surface because of the difference of the lattice mismatch. Therefore, the selective growth of self-organizing InAs islands can be achieved by surface modification of the surface strain and the lattice mismatch of the underlying InGaAs/GaAs layer.

1. Introduction

Semiconductor nanostructures such as InAs quantum dots (QDs) are spontaneously formed during the epitaxial growth. There is much interest in coherent Stranski-Krastanow (SK) islands for the application of the use as QDs to optical and electronic semiconductor devices, and, the analysis of dot structures and optical properties of QDs have been investigated by many research groups [1-5]. Recently, in the growth of QD superlattice (or multi stacked QD) structures, high uniformity in island size and spacing has been reported [6]. The selective growth of QDs is also one of attractive techniques to control the position of QDs and to improve uniformity in dot size. The strain and the lattice mismatch of the epitaxial layer play an important role in the formation of such self-organized islands. Therefore, it is expected that the selective formation of these islands can be realized by means of the strain distribution [7] or the lattice mismatch distribution of the underlying layer.

In this study, the selective self-organization of InAs dots was attempted by using molecular beam epitaxy (MBE) on two kinds of buffer layers, which were the strained InGaAs buffer layer and the mesa stripe of the InGaAs/GaAs multi-quantum-wells (MQWs) buffer layer. Both buffer layers were prepared in order to study relationships between the selective self-organization of InAs dots and the strain distribution or the lattice mismatch distribution of InGaAs/GaAs buffer layers. The selective growth of InAs dots could be achieved, and, its mechanism will be discussed.

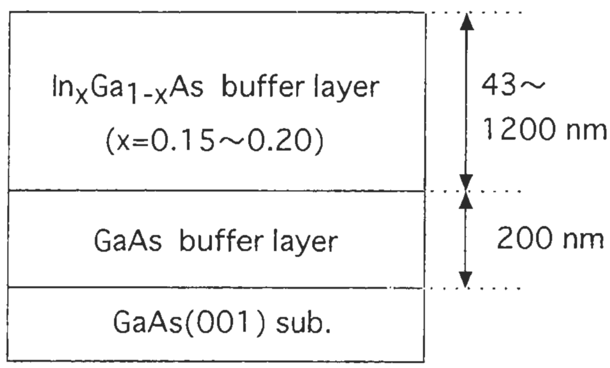

Fig.1 Schematic diagram of the strained InGaAs buffer layer.

2. Experimental Results and Discussion

2-1 Selective self-organization on the strained InGaAs buffer layer

Figure 1 shows the schematic diagram of the strained InGaAs buffer layer prepared by solid-source MBE. InxGa1-xAs (x=0.15~0.20) layers were grown at 500℃ after the GaAs layer (200nm) was grown on the semi-insulating GaAs(001) substrate. The growth rate of the InGaAs buffer layer was maintained at 1.0 monolayer (ML)/s. Prior to the InAs growth, the residual strain of the InGaAs buffer layer was analyzed by double crystal x-ray diffraction (DCXRD).

X-ray rocking curves were obtained from both (004) and (224) reflections, which were measured along both [110] and [1$\bar{1}$0] directions. Figure 2 shows the relationship between the normalized thickness (NT) and the relaxation coefficient of the in-plane lattice space of the In0.18Ga0.82As layers. The NT means a multiple of the critical thickness of the InGaAs layer, which was calculated by Matthews's equation [8]. The relaxation coefficient increases with increasing the thickness of the InGaAs layer. In addition, the residual strain along the [1$\bar{1}$0] direction is much compared with that along the [110] direction. The above phenomenon can be explained by the generation of anisotropic misfit dislocations (α- and β-dislocations) induced at the InGaAs/GaAs heterointerface [9]. Therefore, it is expected that the strain distribution due to misfit dislocations appears on the InGaAs surface and changes by the thickness of the InGaAs buffer layer.

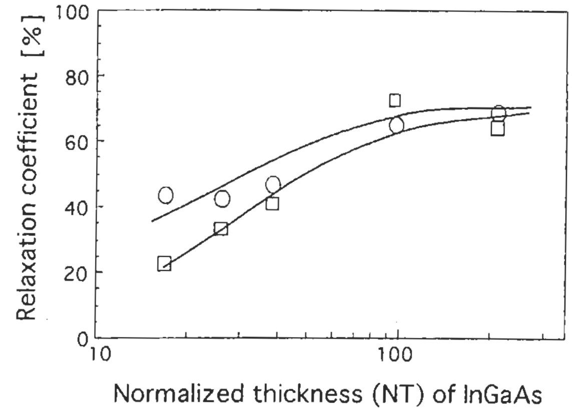

Fig.2 Relationship between the relaxation coefficient of the InGaAs layer and the normalized thickness (NT) of the InGaAs layer. X-ray rocking curves were obtained from both (004) and (224) reflections, which were measured by DCXRD along both [110] (○) and [1$\bar{1}$0] □) directions.

In this experiment, InAs dots were deposited on the above strained InGaAs buffer layer. The reflection high energy electron-beam diffraction (RHEED) pattern changed from the "streak" pattern to the "spot" pattern during the InAs growth, and, as a result, 3-dimensional (3D) InAs islands (dots) were naturally formed on the 2D wetting layer.

Figure 3 shows atomic force microscope (AFM) images of In0.15Ga0.85As surface ((a):177 nm (NT=15)) and InAs dots grown on In0.15Ga0.85As buffer layers ((b):162 nm (NT=12), (c):325 nm (NT=27)). InAs dots are partially grown and align along the [1$\bar{1}$0] direction. Here, it should be noticed that the surface corrugation along the [1$\bar{1}$0] direction is observed on the InGaAs surface before the InAs growth (a). It is well known that such surface corrugation is frequently induced by misfit dislocations. InAs dots are selectively formed on the top of the corrugation [7]. Therefore, this selective self-organization of the InAs dots is attributed to the strain distribution of the InGaAs surface, as expected before. In particular,the selective alignment of

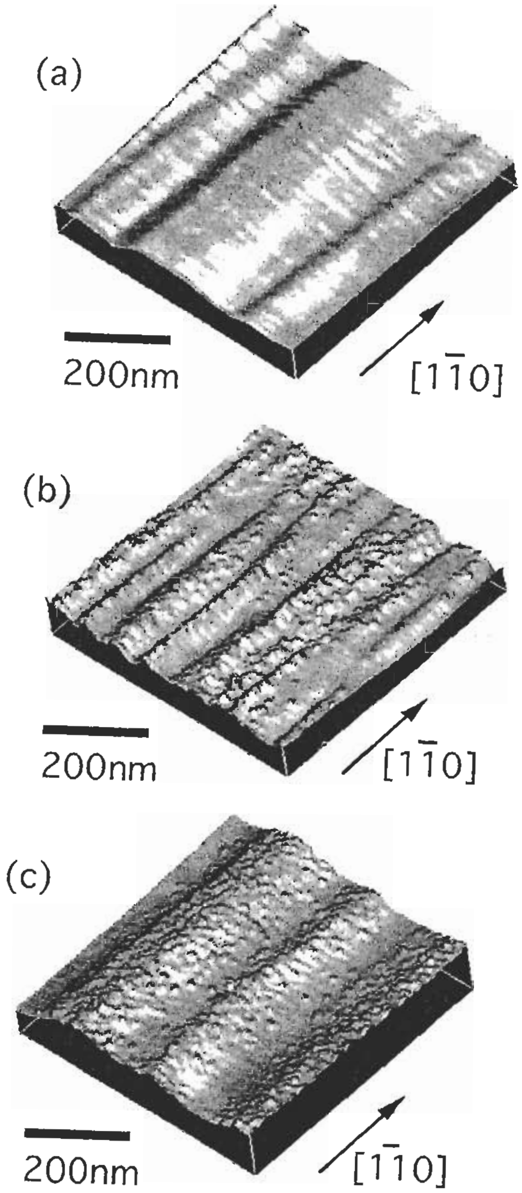

Fig.3 AFM images of the InGaAs surface ((a) 177 nm (NT=15)) and selectively formed InAs dots on strained InGaAs buffer layers ((b) 162 nm (NT=12) and (c) 325 nm (NT=27)). Growth amounts of the InAs were 1.43 ML (b) and 1.67 ML (c), respectively.

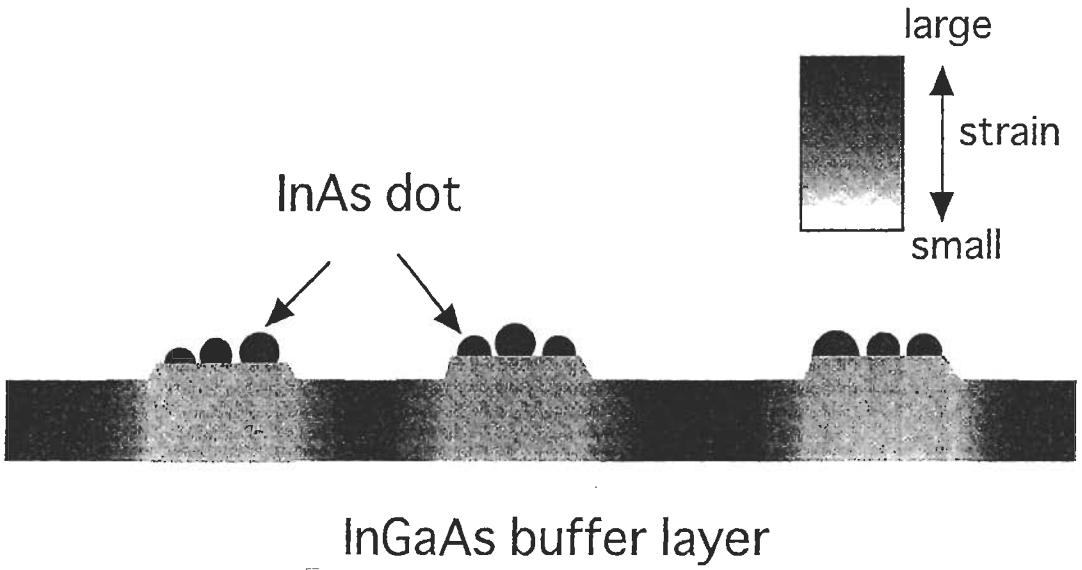

Fig.4 Schematic diagram of $(1\bar{1}0)$ cross-sectional view of selective self-organizing InAs dots on strained InGaAs buffer layer. Layer gives patlerus of InAs dots.

InAs dots along the $[1\bar{1}0]$ direction suggests the anisotropic surface strain. Figure 4 shows the schematic diagram of the $(1\bar{1}0)$ cross-sectional view of InAs dots grown on the strained InGaAs buffer layer. The strain distribution exists on the InGaAs surface, and, InAs dots are selectively grown on the slightly strained (or strain-free) surface. In other words, the growth-free region corresponds to the strongly strained surface, on which the growth of indium adatoms is difficult because of the strain energy and in-plane lattice mismatch. When the thickness of the InGaAs buffer layer was thicker than about 500 nm (NT>40), InAs dots were randomly formed and such selective growth could not be observed [7]. It means that the residual strain is almost relaxed on the whole InGaAs surface. From above results, it is found that self-organizing InAs dots can be controlled by the surface strain of the underlying InGaAs layer, that is, the strain distribution of the underlying layer gives patterns of InAs dots.

2-2 Selective self-organization on the mesa-striped InGaAs MQW buffer layer

Next, figure 5 shows the schematic diagram of the mesa-striped InGaAs/GaAs MQW buffer layer. In0.17Ga0.83As(47 nm)/GaAs (100 nm)

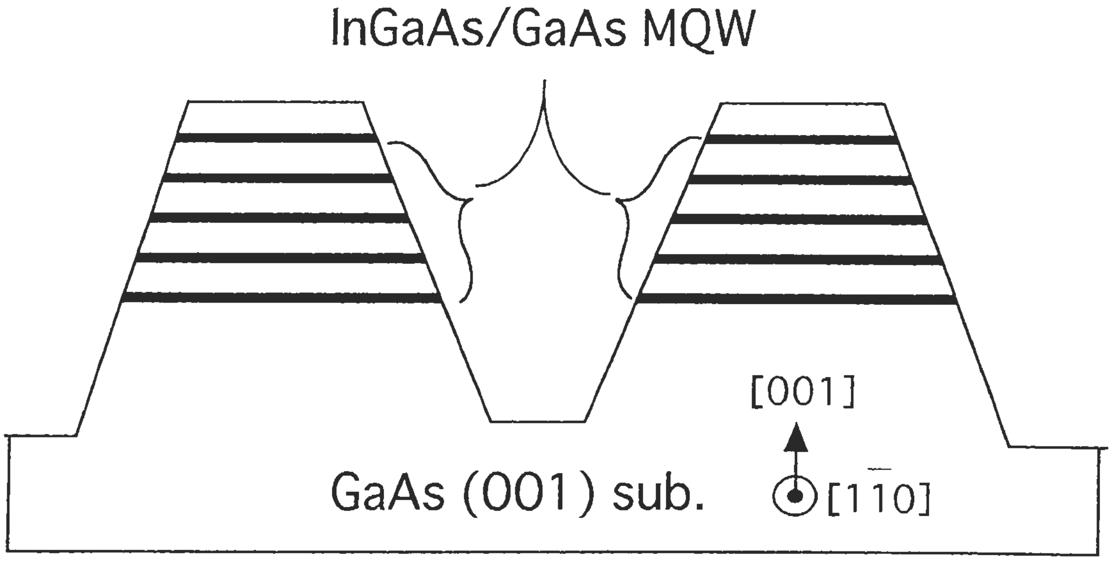

Fig.5 Schematic diagram of the mesa-stripe InGaAs(47 nm)/GaAs(100 nm) MQW buffer layer.

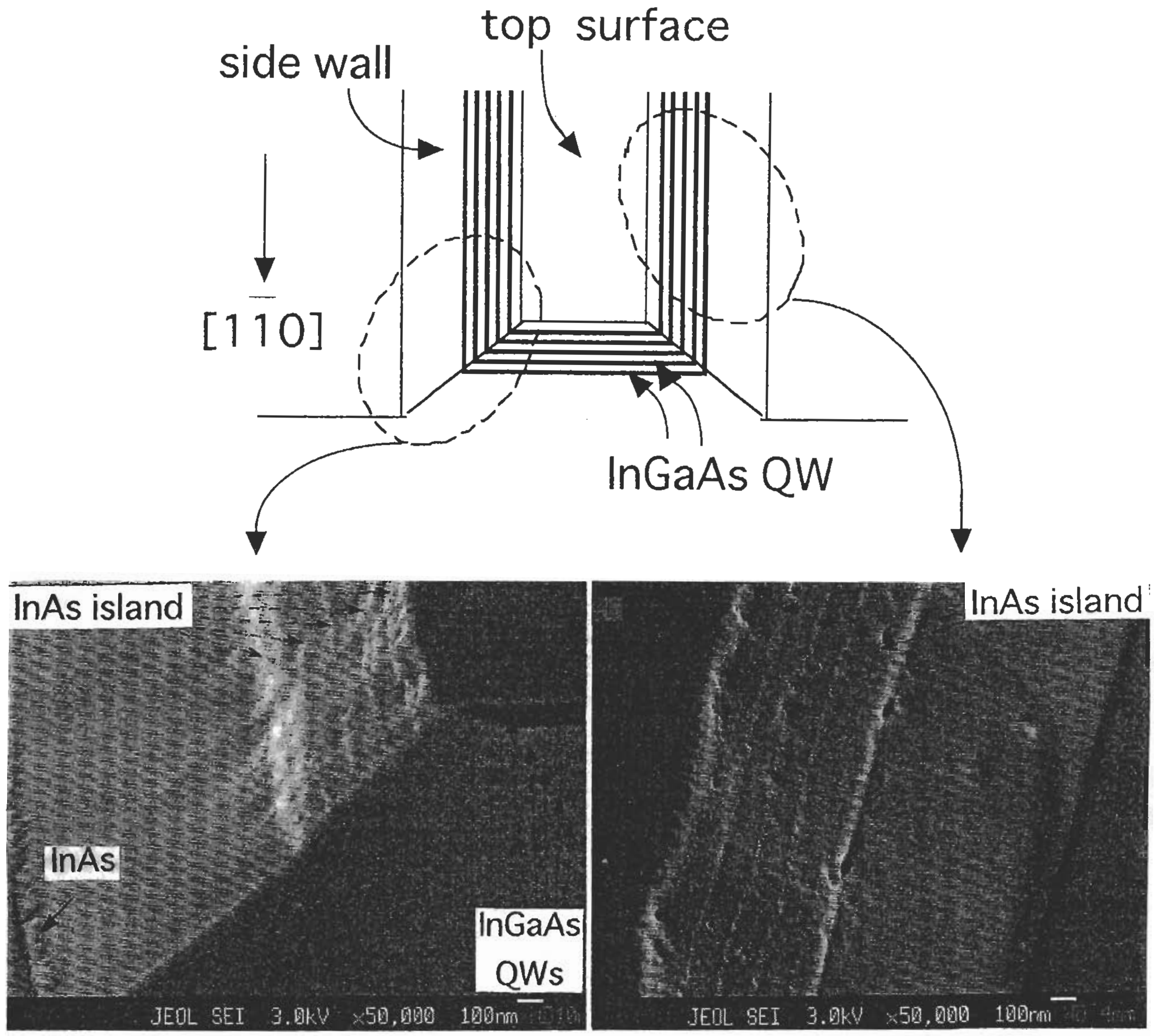

Fig.6 FE-SEM images of InAs dots selectively grown on both side surfaces of mesa stripe.

MQW layer including five QWs was grown by MBE on the GaAs(001) substrate first. The substrate temperature of 500℃. After the stripe-shaped pattern (4 μm width) of the photo-resist film was prepared along the [1$\bar{1}$0] direction on the MQW buffer layer, the opening window area was etched by using the H_2SO_4 solution to form the mesa-stripe pattern of the buffer layer. The InGaAs QW surface and the GaAs barrier surface alternately appear on the side wall of the mesa stripe as shown in Fig.5. In this experiment, it is expected that a difference of the lattice mismatch between the InGaAs QW layer and the GaAs barrier layer influences on the self-organization of InAs dots. InAs dots (2.75 ML) were grown on the mesa-stripe MQW buffer layer by MBE at the substrate temperature of 500 ℃.

Figure 6 shows field emission-scanning electron microscope (FE-SEM) photographs of both side walls of the MQW buffer layer after the InAs growth. InAs islands were clearly observed only on five InGaAs QWs of both side walls, but not on GaAs barrier layers. Since the lattice mismatch of the InGaAs QW for the InAs island is small compared with that of the GaAs barrier layer, the InAs growth on the InGaAs QW is preferable to that on the GaAs layer. Therefore, it suggests that In adatoms on the GaAs barrier surface migrate to the InGaAs QW surface. That is, the selective growth of self-organizing InAs islands can be achieved by such surface modification of the lattice mismatch (or In

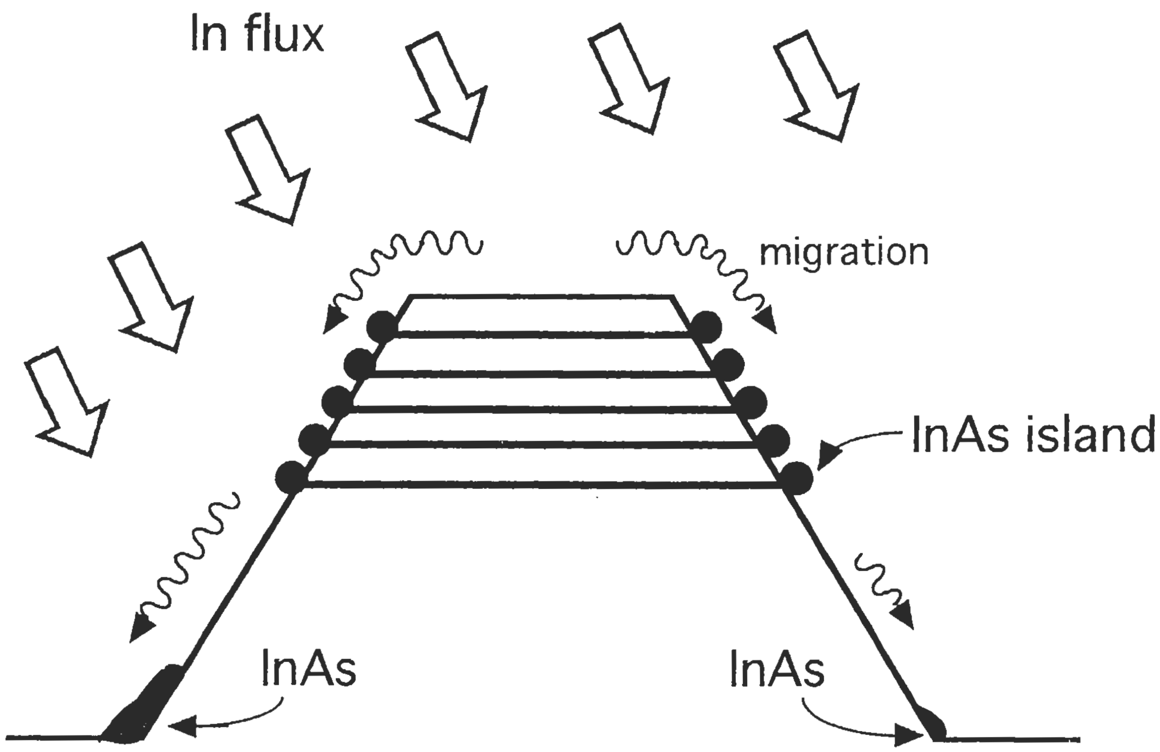

Fig.7 Schematic diagram of cross-sectional view of the mesa stripe during the InAs growth.

composition), which is conveniently designed by the epitaxial growth of the InGaAs/GaAs buffer layer. The connection between quantum dots and quantum wells (or quantum wires) can be realized by using above technique, and, the application to the device structure is expected.

The InAs growth is also observed around the corner of the bottom surface. The growth amount of the InAs grown on the lefthand corner is larger than that on the righthand corner because of the inclined incident beam of the indium flux with respect to the substrate surface. However, the size of InAs islands on both side walls is almost same. Therefore, it indicates that the surface migration of indium adatoms brings about from the top surface to the side wall of the mesa stripe. From the result of Fig. 6, we can estimate that the surface migration length of the indium adatom is about $1\sim2$ μm. The above consideration is diagrammatically shown in Fig. 7.

3. Conclusion

InAs islands were grown on two kinds of the InGaAs/GaAs buffer layer by MBE. One is the strained InGaAs buffer layer grown on the GaAs(001) substrate. The residual strain of the InGaAs buffer layer was analyzed by double crystal x-ray diffraction. The observed anisotropic strain for the <110> direction was induced by anisotropic misfit dislocations generated at the InGaAs/GaAs heterointerface. InAs dots were partially formed on the InGaAs surface and aligned selectively along the <110> direction. It is caused by the strain distribution of the InGaAs surface. That is, InAs dots are formed only on the relaxed InGaAs area, but not on the strained area. It was also found that the selectivity concerning the dot formation of the InAs depends on the thickness of the InGaAs buffer layer.

Another is the mesa stripe of the InGaAs/GaAs MQWs buffer layer, which was prepared by photolithography and wet-chemical etching. InAs islands were formed only on the exposed InGaAs QW surface, but not on the GaAs surface, of the sidewall of the mesa-striped MQW buffer layer. That is, the selective growth of self-organizing InAs islands could be achieved by such surface modification of the lattice mismatch. It was found that In adatoms on the top of the mesa stripe migrate to both side walls and are preferably caught on the InGaAs QW surface because of the small lattice mismatch for the InAs growth. In this experiment,the migration length of the indium adatom was estimated at about $1\sim2$ μm.

The control of the strain distribution and the lattice mismatch of the underlying layer is important for the selective arrangement of self-organizing QDs.

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