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Self Size-Limiting Growth of Uniform InAs Quantum Dots by Molecular Beam Epitaxy

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1. Introduction

The self-assembled semiconductor quantum dots (QDs) have attracted considerable interests for opto-electronic device applications [1] and have been studied actively for more than ten years [2]. The Stranski-Krastanov (SK) growth technique is expected as convenient fabrication method of the high-density coherent QDs and is still an open challenge. In particular, the formation mechanism of SK QDs has not been understood clearly, and, some problems for precise control of the dot formation remain and put some difficulties in the device applications. Among of them, large inhomogeneous broadening of the QD energy levels is an important problem. If the dot size and the shape are automatically limited during the SK growth, the inhomogeneous broadening will be suppressed effectively. Recently, we have demonstrated high uniformity in the size and shape of InAs SK QDs, grown on the GaAs(001) substrate, by self size-limiting (SSL) growth. The photoluminescence (PL) spectra of the uniform InAs QDs revealed narrow linewidth of less than 20 meV [3,4].

In this conference, we present two SSL processes of the 2D and 3D InAs islands in molecular beam epitaxy (MBE) growth via SK mode under low arsenic pressure and low growth rate conditions. Besides the uniform SK growth, we describe deformation of the InAs QDs during the GaAs capping growth. Based on the recent results, uniform formation of InAs QDs is discussed.

2. Self Size-limits of 2D and 3D InAs islands

Figure 1 shows relationship between the height and the [110] lateral size of the InAs islands, grown at low arsenic pressure of 3×10^{-7} Torr and low growth rate of 0.035 ML/s. The InAs coverage was changed from 1.6 ML to 3.0 ML. As the growth proceeds, the lateral size of the 2D InAs platelets increases, and then, is automatically limited at about 25 nm. This SSL behavior is attributed to strained step edges of the platelets. That is, for the large platelets, incorporation probability of indium adatoms is more suppressed at the step edge. Therefore, above SSL process induces the formation of uniform and large 2D platelets if no occurrence of 3D islanding prior to the SSL behavior. The SSL feature strongly depends on the growth conditions: the low arsenic pressure and low growth rate conditions

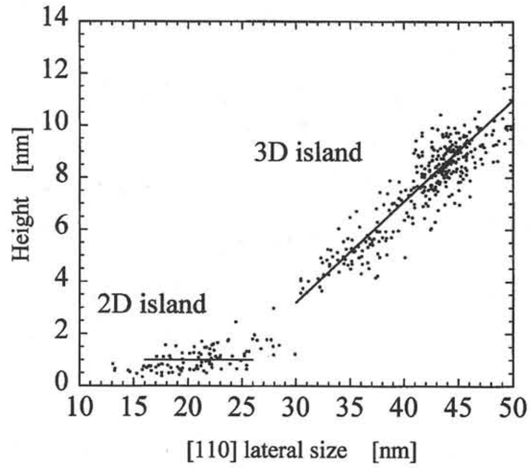

Fig.1. Relationship between the height and the [110] lateral size of InAs islands.

enhanced the SSL effect of the platelets.

Following the first SSL process, the 2D growth mode rapidly transits to the 3D one. Under the low arsenic pressure and low growth rate conditions, the stable facets easily appear on the side wall of the 3D dots, and then, similar pyramidal dots are formed [5,6]. The crystal orientation of the facet was evaluated by using atomic force microscopy (AFM) and reflection high-energy electron-beam diffraction (RHEED) and depended on the growth condition. Particularly, as the growth rate of the InAs dot decreased, the main facet changed from the {136} plane to the {101} plane as typically shown in figure 2. While the size distribution of the 3D InAs dots except the coalescent dots does not change in spite of an increase in the InAs coverage. In other words, the average size of the coherent dots saturates when the coverage is over about 2 ML [3,5]. It should be noticed here that the above SSL behavior concerning the 3D dots appears just after the facet formation. Therefore, it is concluded that the second SSL process is caused by the facet formation: incorporation of indium adatoms is also suppressed on the stable facet surface. From the two-step SSL process, narrow size fluctuation of the 3D InAs dots were successfully obtained. The standard deviation of the uniform InAs dots was about 4 % for the lateral size and about 8 % for the height.

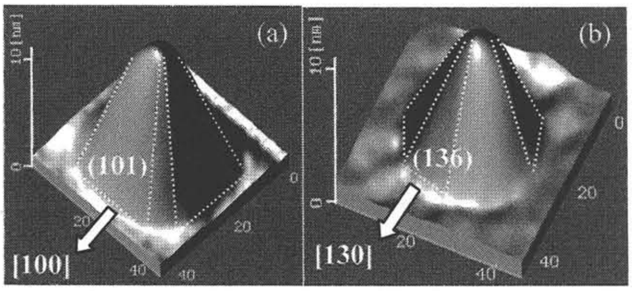

Fig.2. AFM images of InAs 3D dots grown at the growth rate of 0.035 ML/s (a) and 0.16 ML/s (b), respectively.

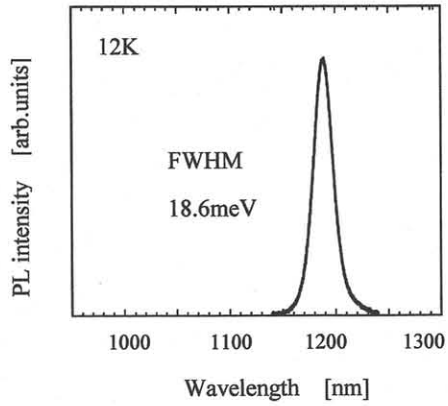

Fig.4. PL spectrum of uniform InAs QDs

3. Deformation of InAs QDs during GaAs capping growth

The embedding growth of the 3D dots frequently modifies the shape of the dots, and, therefore, is also important process for getting uniform QDs. In case of high temperature growth (> 500 ℃) of the GaAs capping layer, the height of the InAs dots drastically decreased. As the result, an inhomogeneous broadening of the QDs was enhanced. While, the low temperature growth (< 430 ℃) provided poor crystal quality of the capping layer. As the result, we found the desirable capping growth at 450-460 ℃ for keeping narrow inhomogeneous broadening [7]. From cross-sectional transmission electron microscope (TEM) observations, it was found that the InAs dot changes from pyramidal shape to dome-like one as shown in figure 3 and that the dot size more decreases for the large dots. The size shrinkage during the GaAs capping growth is mainly due to indium surface segregation and detachment effects, which depend on the strain of the dot edge. The capping growth process was theoretically simulated by kinetic Monte-Carlo method, and, as the results, we pointed out a possibility of the uniform formation by the proper capping growth [8].

From these results, we demonstrated the uniform formation of the InAs QDs with narrow PL linewidth of less than 20 meV as shown in figure 4. Recently, we also fabricated high quality InAs QDs with 1.3 μm light emission by introducing the InGaAs/GaAs hetero-capping layer [9].

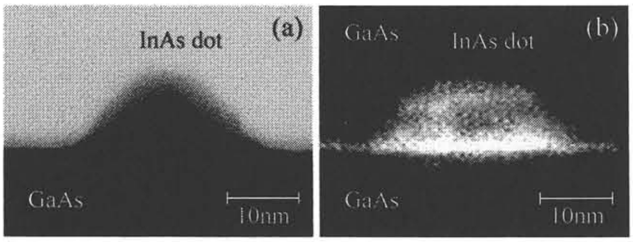

Fig.3. Cross-sectional TEM and scanning TEM images of InAs QDs without GaAs capping layer (a) and with GaAs capping layer (b), respectively.

4. Conclusions

The uniform InAs QDs were grown on the GaAs(001) substrates by conventional MBE via SK growth mode under low arsenic pressure and low growth rate conditions. Two SSL mechanisms played an important role for suppression of the inhomogeneous broadening. The dot size and shape changed during the GaAs capping growth, and, the capping growth process was simulated by kinetic Monte-Carlo method. From these results, we could fabricate the uniform InAs SK-QDs, which revealed narrow PL spectra with less than 20 meV in linewidth.

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