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Self-assembled InAs island formation on GaAs (1 1 0) by metalorganic vapor phase epitaxy

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Abstract

Formation of self-assembled InAs 3D islands on GaAs (1 1 0) substrate by metal organic vapor phase epitaxy has been investigated. Relatively uniform InAs islands with an average areal density of 10^9 $cm^{-2}$are formed at 400 ° C using a thin InGaAs strain reducing (SR) layer. No island formation is observed without the SR layer. Island growth on GaAs (1 1 0) is found to require a significantly lower growth temperature compared to the more conventional growth on GaAs (1 0 0) substrates. In addition, the island height is observed to depend only weakly on the growth temperature and to be almost independent of the V/III ratio and growth rate. Low-temperature photoluminescence at 1.22 eV is obtained from the overgrown islands.

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1. Introduction

Self-assembled InAs three-dimensional (3D) islands and quantum dot (QD) structures grown on GaAs (1 0 0) substrates have been studied widely due to their great prospects in optoelectronic device applications [1]. InAs island formation on substrates with other orientations, especially on GaAs (1 1 0), has also been studied extensively [2–6]. It has been concluded that the growth of an InAs epilayer on GaAs (1 1 0) follows a layer-by-layer mode irrespective of thickness and the strain relaxation occurs by formation of misfit dislocations instead of 3D islands. However, recently it has been reported that the substrate orientation is not an insurmountable obstacle for 3D island formation. A thin strain reducing (SR) layer has been observed to play a very important role in the formation of InAs islands on GaAs (1 1 0). For instance, InAs 3D islands have been successfully grown on GaAs (1 1 0) by using a few monolayers (MLs) of AlAs [7] and InGaAs [8] as a SR layer instead of growing islands directly on GaAs. Although the island growth on GaAs (1 1 0) typically results in a smaller island density than on GaAs (1 0 0), it shows potential for position control of the QDs [9,10] and creating QD arrays by cleaved-edge overgrowth [7,8]. However, all of these studies have been done by molecular beam epitaxy (MBE) and the effects of growth parameters on the island formation and properties are rarely reported in detail.

In this paper, we investigate self-assembled InAs island formation on GaAs (1 1 0) by using metalorganic vapor phase epitaxy (MOVPE). Island properties are studied in a wide range of growth parameters including growth temperature, nominal InAs deposition thickness, V/III ratio, and growth rate. It is shown that relatively uniform 3D islands can be obtained by using a thin InGaAs SR layer. The dependence of the island properties on growth parameters is compared to that of InAs island growth on GaAs (1 0 0).

2. Experimental

The samples were grown on semi-insulating GaAs (1 1 0) substrates in a horizontal MOVPE reactor at atmospheric

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Table 1
The range of parameters used for the growth of InAs layer

T_G (°C)	390–460
d (ML)	1.2–2.5
r_g (ML/s)	0.5–2.5
V/III ratio	3–20

pressure using trimethylindium (TMIn), trimethylgallium (TMGa), and tertiarybutylarsine (TBAs) as precursors for indium, gallium, and arsenic, respectively. A nominally 3 ML thick $In_{0.2}Ga_{0.8}As$ SR layer was grown on a 100 nm thick GaAs buffer layer before the deposition of the InAs layer. The SR layer was grown at the same growth temperature (650 °C) as the buffer layer with a V/III ratio of 23. Before the InAs deposition, the reactor temperature was stabilized at the InAs growth temperature (390–460 °C) under a TBAs flow to protect the surface. The InAs layer was grown at different growth temperature, layer thickness, growth rate and V/III ratio. The range of the InAs layer growth parameters are listed in Table 1. Growth temperarure (T_G) is 400 °C, layer thickness (d) is 1.7 ML, growth rate (r_g) is 1.5 ML/s, and V/III ratio is 5 when they are not varied. For comparison, the same structures were also grown on GaAs (1 0 0) substrate in a separate growth run due to the different growth temperature. For the study of the optical properties, a set of samples were fabricated by covering the islands by a 50 nm thick GaAs layer grown at the same temperature. The temperatures mentioned in this paper are thermocouple readings [11] and V/III ratios are molar flow ratios.

The morphology of InAs islands was characterized using contact-mode atomic force microscopy (AFM). The AFM tips are non-conductive silicon nitride tips with diameter of 20 nm. The low-temperature (10 K) continuous-wave photoluminescence (PL) measurements were conducted by utilizing a diode-pumped frequency-doubled Nd:YVO_4 laser emitting at 532 nm for excitation. A liquid-nitrogen-cooled germanium detector and standard lock-in techniques were used to record the PL spectra.

3. Results and discussion

The influence of the SR layer on the island formation was investigated first. Two monolayers of InAs was deposited on GaAs (1 1 0) and (1 0 0) substrates at 460 ° C with and without a 3 ML thick $In_{0.2}Ga_{0.8}As$ SR layer. 3D InAs islands were formed on GaAs (1 0 0) in both cases. By contrast, islands were observed on GaAs (1 1 0) only when the InGaAs SR layer was used. Island growth on GaAs (1 1 0) was not achieved without the SR layer even at a lower growth temperature of 400 °C. In addition, at 400 °C, no obvious difference was observed on GaAs (1 1 0) samples when the SR layer thickness was changed from 3 ML to 1 ML. The probable main role of the InGaAs SR layer on GaAs (1 1 0) substrate is controlling strain and dislocation formation by forming In(Ga)As alloy rather than pure InAs in the beginning of the island deposition. Thus, the preferred route for strain relaxation is the formation of 3D islands [8]. Based on these results, a nominally 3 ML thick $In_{0.2}Ga_{0.8}As$ layer was utilized as a SR layer for all the subsequent samples.

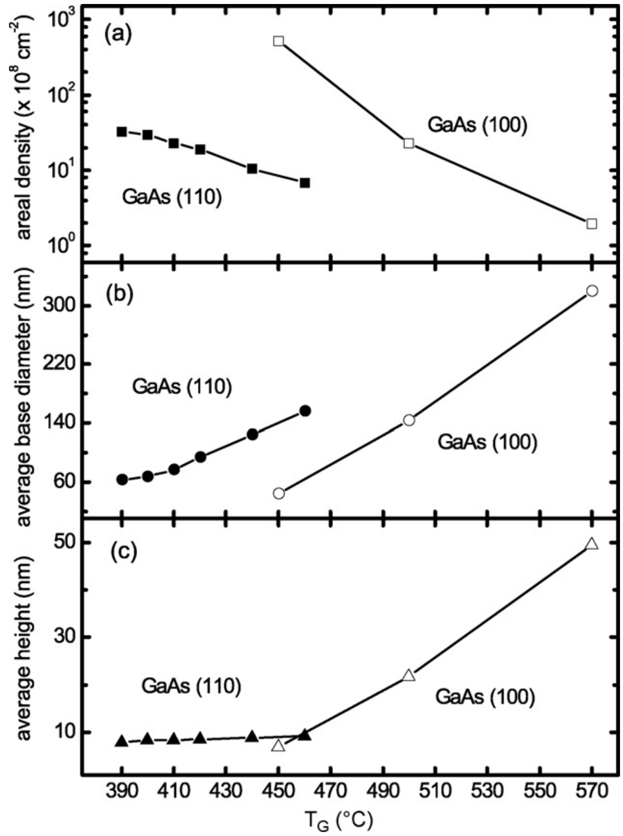

Fig. 1. (a) The areal density, (b) average base diameter, and (c) average height of InAs islands on GaAs (1 1 0) and GaAs (1 0 0) as the function of the growth temperature (d = 1.7 ML, r_g = 1.5 ML/s, and V/III ratio is 5).

Fig. 1 shows the areal density and the average base diameter and height of InAs islands on GaAs (1 1 0) and (1 0 0) substrates as a function of the growth temperature. The overall trends are similar irrespective of the substrate orientation: the island density decreases and the island size increases when the growth temperature is increased, as expected [12]. However, some clear differences can also be observed.

First, in order to obtain successful 3D island growth on the (1 1 0) substrate one has to use a considerably lower growth temperature. The island density on GaAs (1 1 0) is about $10^8$to 10^9 cm^{-2} when the growth temperature is varied in the range of 390–460 ° C (Fig. 1(a)). Above 460 °C, the islands become very large (up to one micron in base diameter) and their density is very small ($<10^6$ cm^{-2}, not shown in Fig. 1). No islands were formed below 390 °C. For the (1 0 0) substrate, growth at 460 °C resulted in about two orders of magnitude higher island density (5×10^{10} cm^{-2}) than on the (1 1 0) substrate. At lower growth temperatures, lower than 450 °C, the (1 0 0) sample surface became very rough due to coalescence of the high density islands.

Secondly, the base diameter and average height of the islands grown on the (1 0 0) substrate increase rapidly with the growth temperature while the islands on the (1 1 0) substrate, on the other hand, grow laterally rather than vertically (Fig. 1(b) and (c)). In fact, the average island height on the (1 1 0) substrate remains almost unchanged ($\sim$8 nm). This behavior differs from the conventional 3D island growth on (1 0 0)

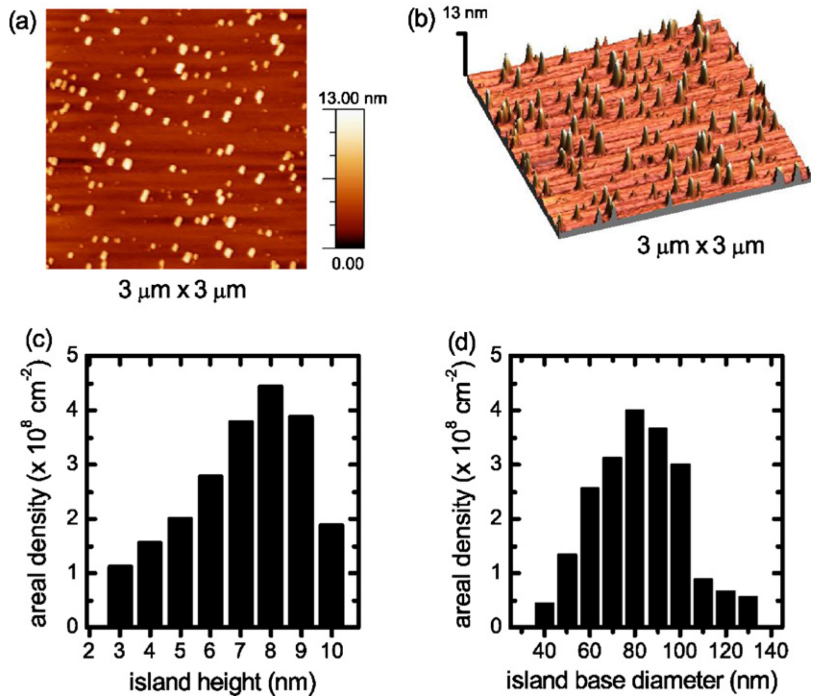

Fig. 2. (a) 2D and (b) 3D images from AFM scans of 1.5 ML InAs islands grown on GaAs (1 1 0) at 400 ° C with V/III ratio of 5. (c) Height and (d) base diameter distribution histograms of the islands ($T_G = 400$ °C, $d = 1.5$ ML, $r_g = 1.5$ ML/s, and V/III ratio is 5).

substrates. It might be caused by the energy barrier for the nucleation of a misfit dislocation [13] or/and elastic strain effect [14], which depends on the substrate orientation [15] and results in a smaller critical thickness of dislocation-free islands and causes no further increase in the height but the numbers of the islands on (1 1 0) orientation.

Fig. 2 shows the AFM images as well as island height and base diameter distribution histograms of typical InAs islands (1.5 ML InAs deposited at 400 °C) on GaAs (1 1 0). The aspect ratio (height/base diameter) is on average around 0.1. The aspect ratio of a typical island on (1 0 0) GaAs, grown at 460 °C, is about 0.15. These values coincide with the reported values of InAs/GaAs island aspect ratios 0.1–0.25 [16].

Properties of InAs islands on GaAs (1 1 0) were also studied by changing other growth parameters, such as nominal thickness of InAs layer, V/III ratio and growth rate. Fig. 3 shows the areal density and the average base diameter and height of InAs islands on GaAs (1 1 0) substrates as a function of the nominal thickness of the InAs layer. No 3D islands were observed at 400 ° C when the nominal thickness was less than 1.5 ML. This critical thickness for island formation is larger than that of islands on GaAs (1 0 0) (about 0.7 ML at 460 °C). It may be the result of the dependence of the critical thickness of island nucleation on substrate orientation in highly strained InAs/GaAs heterostructure [17]. When the thickness is increased further, the island density is increased, but, unlike on the (1 0 0) substrate, the islands become smaller in size. We assume that more InAs was deposited between the already-existing islands rather than on top of them due to the energy barrier or the energy cost associated with adatom incorporation in strained island which is determined by the size of the island [14]. As a result, the larger islands (with higher strain) tend to grow slower than smaller islands. This also leads to new island formation.

Fig. 4 shows the areal density and the average base diameter of InAs islands on GaAs (1 1 0) as a function of the V/III ratio

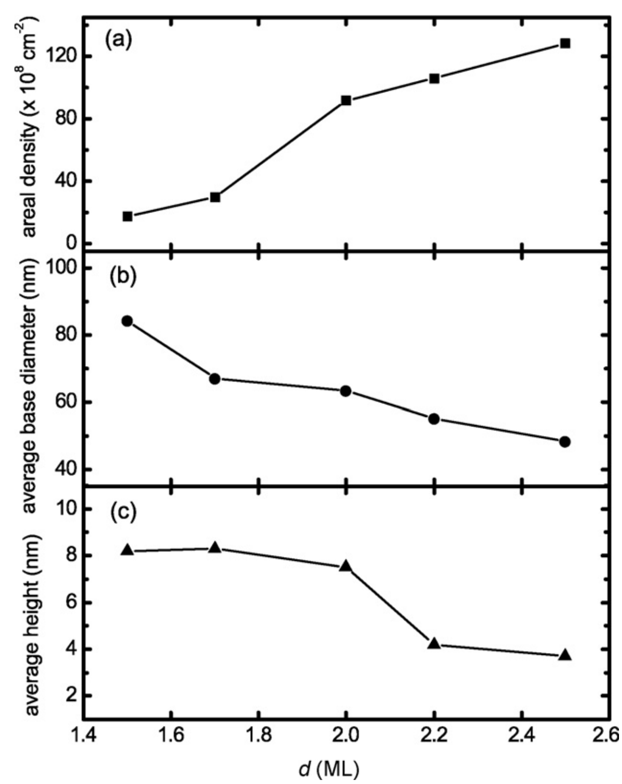

Fig. 3. (a) The areal density, (b) average base diameter, and (c) average height of InAs islands on GaAs (1 1 0) as the function of the nominal thickness of InAs layer. T_G =400 °C, r_g =1.5 ML/s, and V/III ratio is 5.

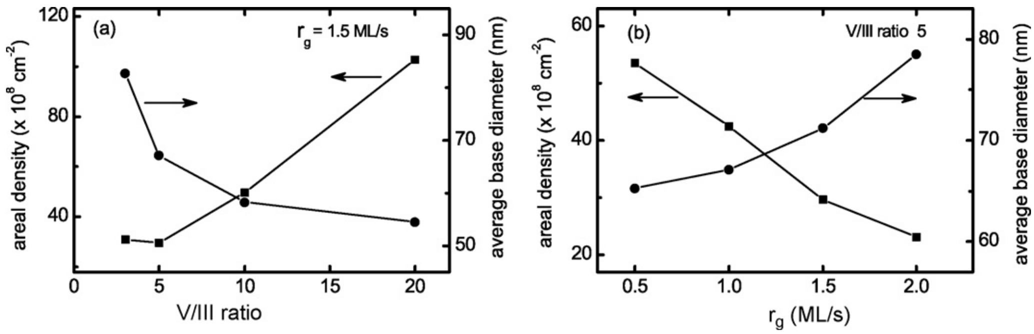

Fig. 4. The areal density and the average base diameter of InAs islands on GaAs (1 1 0) substrates as a function of (a) V/III ratio and (b) growth rate of InAs layer (T_G =400 °C, d =1.7 ML).

and growth rate of the InAs layer. In both cases, the average island height remains almost unchanged at roughly 8 nm (not shown in the figure) irrespective of the V/III ratio and growth rate changes. When the same amount of InAs was deposited at a larger V/III ratio, the island density increased and island base diameter decreased. This might be the result of shorter migration length of In atoms on the surface in the arsenic rich condition. A rough calculation, based on the AFM results, of the total island volume in a certain area shows that the island volume is larger when the same thickness of InAs layer is deposited with high V/III ratio. This indicates that the thickness of 2D InAs wetting layer before 3D island formation depends on the amount of the incoming arsenic atoms, or, probably, In and Ga atoms from the SR layer participate in forming more In(Ga)As islands in arsenic rich condition. The island density increases and island base diameter decreases when the growth rate is decreased. At the lower growth rate, the deposition time is longer and consequently the nucleation of new islands will be enhanced.

The optical properties of buried InAs islands grown on GaAs (1 1 0) were studied by low-temperature PL. Fig. 5 shows the PL spectrum from a sample having 1.2 ML of InAs deposited at 460 °C. The PL spectrum of a structure grown without InAs deposition is shown as a reference. The PL peak from the InGaAs SR layer is seen in both samples around 1.35 eV. The PL peak from the InAs or InGaAs islands is observed at 1.22 eV and has a full width at half maximum of about 100 meV. The broadness of the PL peak may be due to the inhomogeneity of the island size or the formation of $In_xGa_{1-x}As$ islands with a wide range of x.

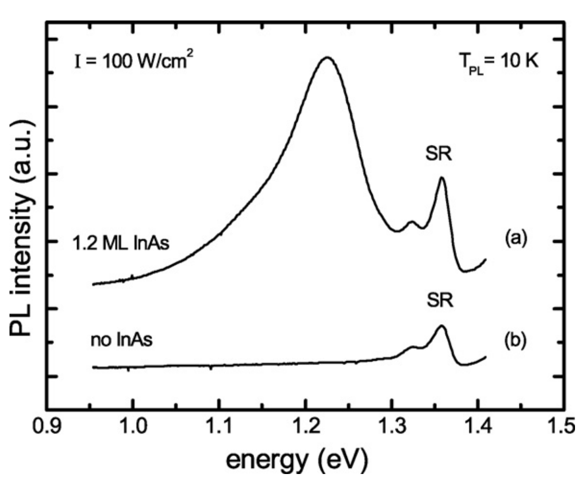

Fig. 5. Low-temperature (10 K) PL spectra from capped samples grown on GaAs (1 1 0): (a) 1.2 ML InAs; (b) no InAs grown at 460 °C. The laser excitation density is 100 W/cm^2.

4. Conclusion

In summary, the formation of InAs 3D islands on GaAs (1 1 0) by MOVPE was investigated. The island properties were studied in a wide range of growth parameters and compared to those of similar islands grown on GaAs (1 0 0). InAs islands with an average density of 10^9 cm^{-2} were successfully formed by using a 3 ML thick InGaAs SR layer. No island growth was observed without the SR layer. In general, InAs island growth on GaAs (1 1 0) required a significantly lower growth temperature and resulted in smaller island density than on GaAs (1 0 0). The island height was also observed to depend only weakly on the growth temperature. In addition, the island size decreased when the nominal thickness was increased, but remained almost unchanged by the V/III ratio or the growth rate. Buried islands exhibited a low-temperature PL peak at 1.22 eV.

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