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Scanning tunneling miscroscopy study of InAs islands grown on GaAs(001) substrates

Osamu Suekane *, Shigehiko Hasegawa, Masahiro Takata, Toshiko Okui, Hisao Nakashima

The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Osaka 567-0047, Ibaraki, Japan

Abstract

Scanning tunneling microscopy (STM) connected to molecular beam epitaxy (MBE) has been used to investigate InAs islands and wetting layers (WLs) on GaAs(001) substrates. STM results reveal that the size and density of InAs islands depend strongly both on the growth temperature and growth rate of InAs. With increasing the growth temperature, the island density becomes lower and the size larger. With increasing the growth rate, the island density becomes higher and the size smaller. Moreover, it is found that two-step growth by varying the growth temperature under a fixed growth rate results in the bimodal distribution of the InAs island-size. These results indicate that controlling the growth temperature and growth rate makes it possible to control the size distribution of InAs islands as well as the size and density of InAs islands. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: GaAs; InAs; Island; Quantum dot; Scanning tunneling microscopy; Molecular beam epitaxy

1. Introduction

Self-assembled quantum dots have attracted great interest because of both their fundamental properties and applications to optoelectronics. In particular, semiconductor lasers based on InAs quantum dots have been studied by many groups since these structures offer the prospect of high characteristic temperature, low threshold current density and lasing at 1.3 μm [1–3]. To realize such device applications, it is necessary to control the size, density and spatial arrangement of InAs islands which are very sensitive to the growth conditions, namely, substrate temperature [4,5], V:III flux ratio [6], growth rate [7] and growth interruption after the growth of InAs [8,9]. Therefore, it is very important to obtain the detailed knowledge about the formation mechanisms of InAs islands on GaAs. As for the spatial arrangement, we have already shown that InAs islanding occurs at nonatomic steps on wetting layers (WLs) [10]. We have also reported that for islands grown by 1.6 monolayers (ML) InAs deposition at 450 °C, post-annealing at 450 °C in an As_4 atmosphere causes dissolving of the InAs islands, while for larger islands obtained by 2.0 ML InAs deposition at 450 °C, the post-annealing leads to coarsening of the islands [11].

In this study, we have investigated the growth temperature and growth rate dependence of InAs islands grown on GaAs(001) substrates using reflection high-energy electron diffraction (RHEED), scanning tunneling microscopy (STM) and photoluminescence (PL) to control the size and density of InAs islands.

2. Experimental procedure

All samples were grown by molecular beam epitaxy (MBE) connected to STM. Before growth of a GaAs buffer layer and InAs layers, chemically etched substrates were thermally cleaned at 630 °C for 30 min in an As_4 atmosphere. During the 200 nm GaAs buffer layer growth at 580 °C, the surface exhibited a (2 × 4) RHEED pattern. The (2 × 4) surface changed to a c (4 × 4) surface during lowering the substrate tempera-

* Corresponding author. Tel.: +81-6-6879-8411; fax: +81-6-6879-8414.

E-mail address: osamu11@sanken.osaka-u.ac.jp (O. Suekane).

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ture at or below 480 °C. 1.6 ML of InAs were deposited on the GaAs(001) c(4 × 4) surface. The formation of InAs islands was confirmed by the appearance of facet-related streaks in the RHEED patterns. The coverage of InAs was estimated from the reported result that the facet-related RHEED pattern appears at a coverage of 1.6 ML [12,13], where 1 ML is defined by atom density of GaAs(001) surfaces. InAs islands were grown under two series of the growth conditions: one is by varying the growth temperature (420, 450, 480 °C) under a growth rate of 0.067 ML·s^{-1}, the other is by varying the growth rate of InAs (0.025, 0.067, 0.133 ML·s^{-1}) under a growth temperature of 450 °C. For the STM observations, samples were cooled down immediately to room temperature after the growth of InAs, and then transferred to the STM chamber through an UHV tunnel.

To investigate optical properties, 50 nm GaAs cap layers were grown on the InAs islands, which were grown under the same growth conditions as those for the STM observation. A GaAs cap layer was grown at the InAs growth temperature without growth interruption to suppress the change of size and density of InAs islands. PL measurements were carried out at 5 K using an Ar ion laser line at 514.5 nm as an excitation source. Signals were detected with a cooled CCD camera.

3. Results and discussion

Fig. 1a–c show STM images taken for the GaAs(001) surfaces covered with InAs islands and WLs formed at 420, 450 and 480 °C, respectively. The growth rate of InAs is 0.067 ML·s^{-1}. Scan area is 400 × 400 nm. InAs islands are elongated along [1$\bar{1}$0] direction, as is previously reported by several groups [14,15]. Step structures of WLs are clearly observed. Fig. 2a–d show the growth temperature dependence of the length along [110] direction, length along [1$\bar{1}$0] direction, height and density of InAs islands estimated from the STM images, respectively. It is found that the size and density of islands depend strongly on the growth temperature of InAs. With increasing the growth temperature, the island density becomes lower and the size larger. From PL results [16], a PL peak shift to longer wavelength is observed with increasing the InAs growth temperature. This shift agrees with the STM result that larger islands are grown at higher growth temperature, as shown in Figs. 1 and 2. Higher desorption rate and longer migration length at higher growth temperature cause the larger size and lower density of InAs islands.

Fig. 3a–c show STM images taken for the samples grown at 450 °C with three different growth rates of

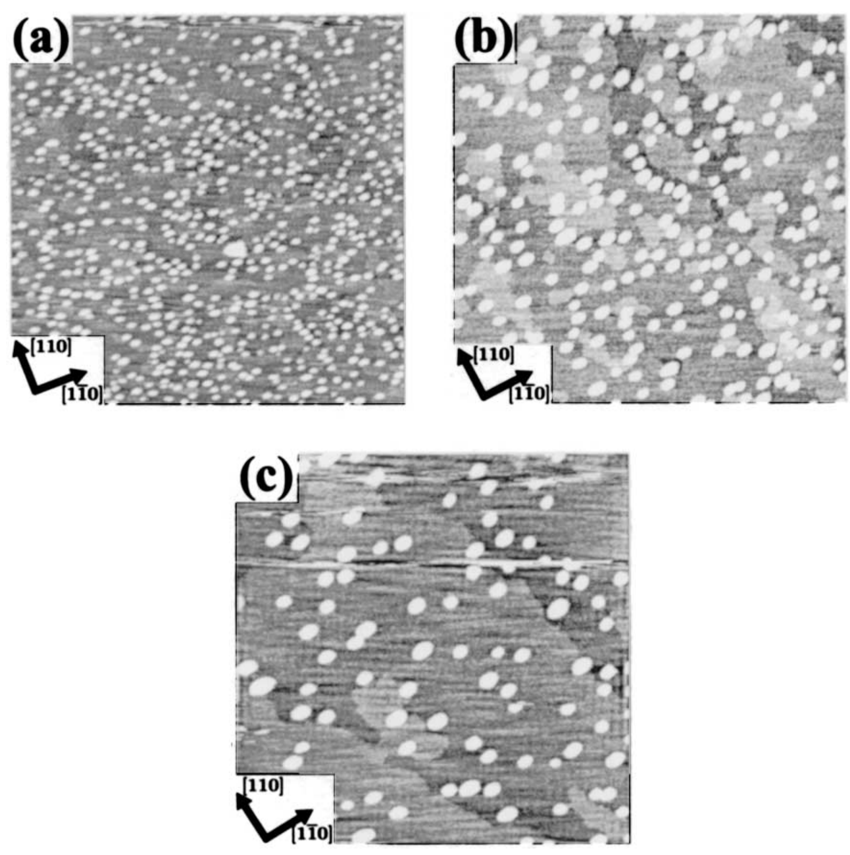

Fig. 1. STM images taken for the GaAs(001) surfaces covered with InAs islands and WLs formed at (a) 420 °C (V_s = 2.0 V, I_t = 1.0 nA), (b) 450 °C (V_s = 2.0 V, I_t = 1.0 nA) and (c) 480 °C (V_s = 2.0 V, I_t = 2.0 nA), respectively. Scan area is 400 × 400 nm.

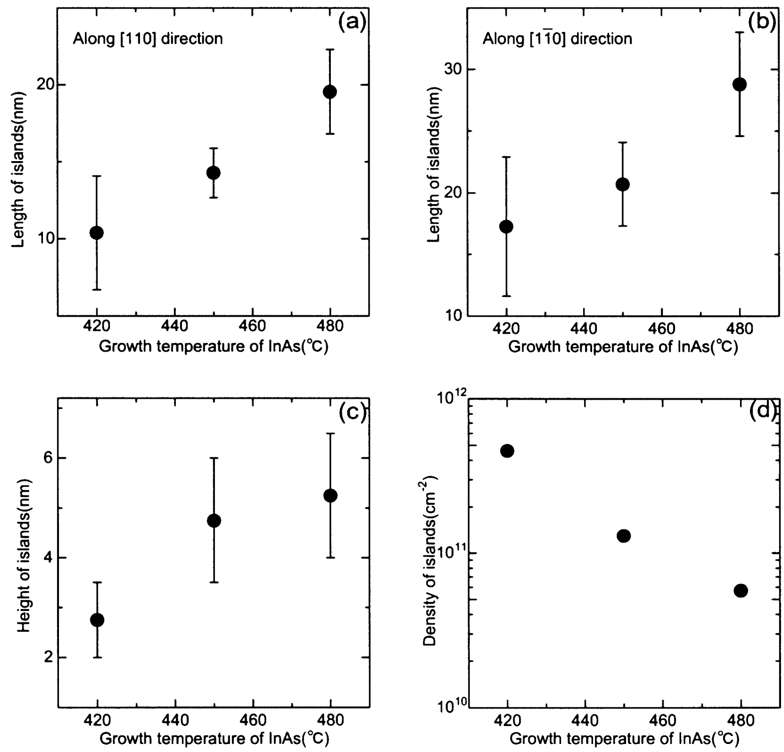

Fig. 2. The growth temperature dependence of the length along [110] direction (a), length along [1$\bar{1}$0] direction (b), height (c) and density of InAs islands (d) estimated from the STM images, respectively.

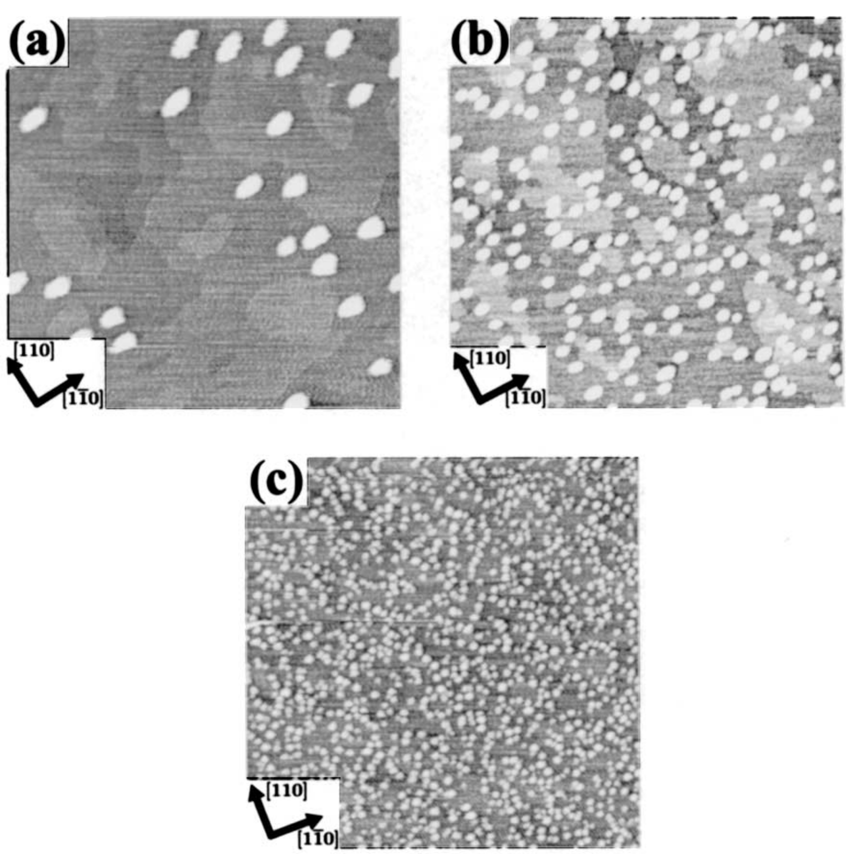

Fig. 3. STM images taken for the samples grown at 450 °C with three different growth rates of (a) 0.025 ML·s^{-1} ($V_s = 2.0$ V, $I_t = 1.5$ nA), (b) 0.067 ML·s^{-1} ($V_s = 2.0$ V, $I_t = 1.0$ nA) and (c) 0.133 ML·s^{-1} ($V_s = 2.5$ V, $I_t = 1.0$ nA), respectively. Scan area is 400 × 400 nm.

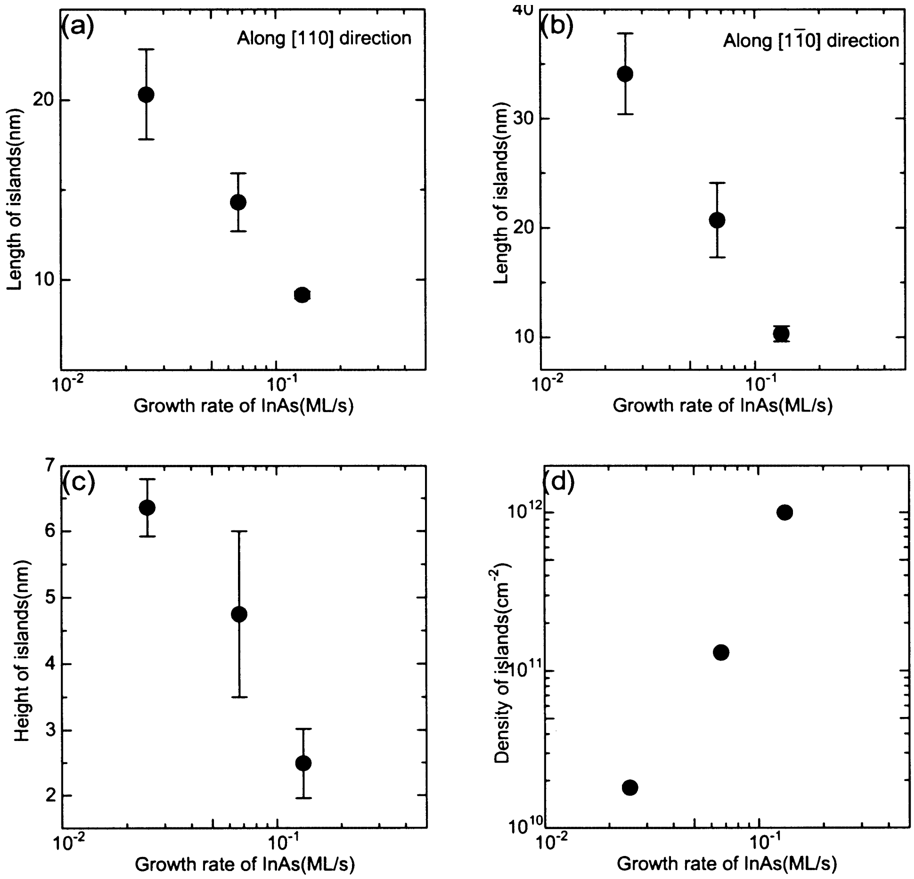

Fig. 4. The growth rate dependence of the length along [110] direction (a), length along [1$\bar{1}$0] direction (b), height (c) and density of InAs islands (d) estimated from the STM images, respectively.

0.025, 0.067 and 0.133 ML·s^{-1}, respectively. Scan area is 400 × 400 nm. Fig. 3b is identical to Fig. 1b. Fig. 4a–d show the growth rate dependence of the length along [110] direction, length along [1$\bar{1}$0] direction, height and density of InAs islands estimated from the STM images, respectively. The island size and density also depend strongly on the growth rate. With increasing the InAs growth rate, the InAs island density becomes higher and size smaller. From PL results (not shown), a PL peak shift to shorter wavelength is observed with increasing the InAs growth rate. This shift agrees with the STM result that smaller islands are grown at larger growth rate, as shown in Figs. 3 and 4. The growth rate dependence of InAs island formation can be explained by considering adsorption and desorption of InAs. Higher growth rate means higher adsorption rate. The density of In adatom becomes higher at higher adsorption rate. This leads to large nucleation probability. Then, even a small island can stably remain on the surface at higher growth rate.

Fig. 5 summarizes the STM results. With increasing the growth temperature and decreasing the growth rate of InAs, the density of islands becomes low and the size of islands becomes large. On the other hand, with decreasing the growth temperature and increasing the growth rate of InAs, the island density becomes higher and size smaller. From this, the island size and density can be controlled by varying growth temperature and growth rate. It should be noted that the size of islands was independent of when the STM images were taken, e.g. 2 h or 2 days after the growth.

From the present result, it is expected that two-step growth by varying the growth temperature under a constant growth rate leads to a bimodal distribution of the InAs island-size. Fig. 6a shows a STM image

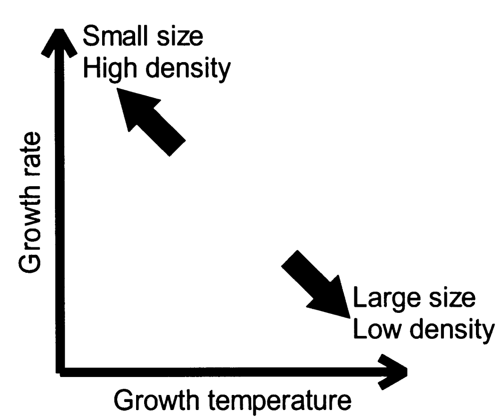

Fig. 5. This figure summarizes the STM results.

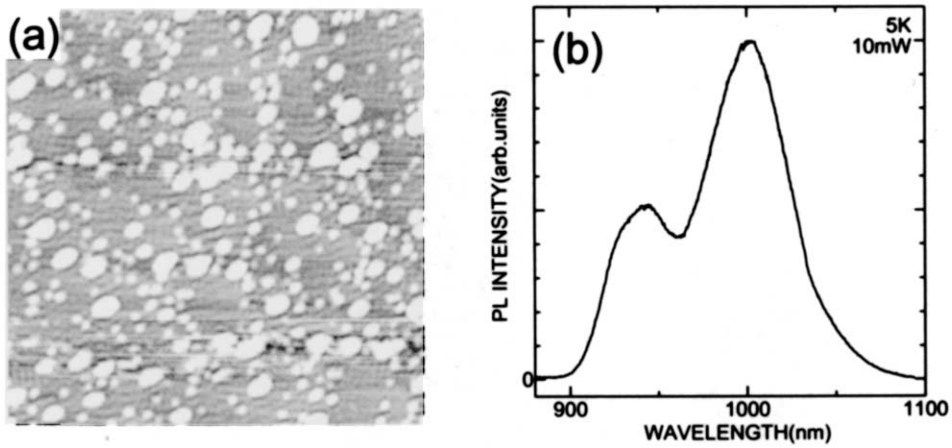

Fig. 6. A STM image (a) ($V_s = 2.8$ V, $I_t = 1.0$ nA, 400 × 400 nm) for the GaAs(001) surfaces covered with InAs islands grown by two-step growth mode. A PL spectrum (b) of InAs quantum dots grown in the two-step growth mode.

(400 × 400 nm) for the GaAs(001) surfaces covered with InAs islands grown by two-step growth mode. Initially, 1.6 ML of InAs was grown at 480 °C. Then, samples were cooled down immediately to 420 °C and 0.5 ML of InAs were grown. The growth rate of InAs was fixed at 0.067 ML·s^{-1}. From the STM image, it can be seen that InAs islands having a bimodal distribution of the size are grown. One is a group of larger islands 17-nm long along [110], 25-nm long along [1$\bar{1}$0] and 8-nm high in average, the other is a group of smaller islands 10-nm long along [110], 15-nm long along [1$\bar{1}$0] and 3-nm high in average. In comparison to the growth temperature dependence of InAs islands, it is found that larger (smaller) islands grown in the two-step growth mode are almost the same in size as islands grown at 480 °C (420 °C) except that larger islands are higher by 3 nm in average than islands grown at 480 °C. Fig. 6b shows a PL spectrum of InAs quantum dots grown in the two-step growth mode. For PL measurements, 50 nm GaAs cap layers were grown at 420 °C after the growth of InAs quantum dots in the two-step growth mode. The PL spectrum displays two significant peaks, resulting from the bimodal distribution of the island size. The smaller QDs peak observed at around 940 nm is almost the same in wavelength as QDs formed at 420 °C. In contrast, the larger QDs peak observed at around 1000 nm has longer wavelength than that from islands formed at 480 °C. This result is consistent with the STM observation that larger islands grown in the two-step growth mode are larger in height than islands formed just at 480 °C.

4. Conclusions

STM connected to MBE has been used to investigate InAs island formation on GaAs(001) substrates. STM results reveal that the size and density of InAs islands depend strongly both on the growth temperature and growth rate of InAs. With increasing the growth temperature, the island density becomes lower and size larger. With increasing the growth rate, the island density becomes higher and size smaller. Moreover, it is found that two-step growth by varying the growth temperature under a fixed growth rate results in the bimodal distribution of the InAs island-size. These results indicate that controlling the growth temperature and growth rate of InAs makes it possible to control the size and density of InAs islands.

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References

[1] Y. Arakawa, H. Sakaki, Appl. Phys. Lett. 40 (1982) 939.
[2] H. Sakaki, Jpn. J. Appl. Phys. 28 (1989) L134.
[3] L.V. Asryan, R.A. Suris, IEEE J. Quantum Electron. 34 (1998) 841.
[4] H.W. Ren, K. Nishi, S. Sugou, Y. Masumoto, Jpn. J. Appl. Phys. 37 (1998) 1548.
[5] H. Saito, K. Nishi, S. Sugou, Appl. Phys. Lett. 74 (1999) 1224.
[6] G. Solomon, J.A. Trezza, J.S. Harris, Appl. Phys. Lett. 66 (1995) 3161.
[7] Y. Nakata, K. Mukai, M. Sugawara, K. Ohtsubo, H. Ishikawa, N. Yokoyama, J. Cryst. Growth 208 (2000) 93.
[8] H.W. Ren, K. Nishi, S. Sugou, Y. Masumoto, Jpn. J. Appl. Phys. 36 (1997) 4118.
[9] Z.D. Lu, J.Z. Xu, B.Z. Zheng, Z.Y. Xu, W.K. Ge, Solid State Commun. 109 (1999) 649.
[10] S. Hasegawa, K. Arakawa, M. Tanaka, H. Nakashima, J. Cryst. Growth (2001), in press.
[11] O. Suekane, S. Hasegawa, M. Tanaka, T. Okui, H. Nakashima, Appl. Surf. Sci., in press.
[12] H. Schuler, K. Eberl, Microelectron. J. 30 (1999) 341.

[13] C. Heyn, D. Endler, K. Zhang, W. Hansen, J. Cryst. Growth 210 (2000) 421.
[14] Y. Nabetani, T. Ishikawa, S. Noda, A. Sasaki, J. Appl. Phys. 76 (1994) 347.
[15] Y. Hasegawa, H. Kiyama, Q.K. Xue, T. Sakurai, Appl. Phys. Lett. 72 (1998) 2265.
[16] O. Suekane, T. Okui, M. Takata, S. Hasegawa, H. Nakashima, in press.