Sharp Interfacial Structure of InAs/InP Quantum Dots Grown by a Double-Cap Method: A Cross-Sectional Scanning Tunneling Microscopy Study

Y. Akanuma[1], I. Yamakawa[1], Y. Sakuma[2], T. Usuki[3], and A. Nakamura[1]

[1]*Department of Applied Physics, Nagoya University, Chikusa-ku, Nagoya 464-8603, Japan*
[2]*National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*
[3]*Fujitsu Laboratories Ltd., 10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan*

Abstract. Interfacial properties of InAs quantum dots (QDs) grown by a double-cap method in metalorganic chemical vapor deposition have been investigated by cross-sectional scanning tunneling microscopy (XSTM). XSTM images reveal that top and bottom interfaces of the InAs QD are extremely sharp. QDs with a monolayer-stepped height in the range 6–14 ML are observed, which indicates that the double-cap method can produce QDs with a well-defined height.

Keywords: quantum dots, interfacial structure, scanning tunneling microscopy, III-V compounds semiconductor
PACS: 68.37.Ef, 61.46.-w, 68.35.Ct

INTRODUCTION

Single InAs quantum dots (QDs) have recently attracted much attention because of potential applications in quantum information devices for optical telecommunication[1,2]. Changing a height of single InAs QDs on InP, the photoluminescence wavelength can be selected in the range from 1.3 to 1.5 μm. A technique called as a "double-cap" method has been proposed to control a height of InAs QDs on a scale of several monolayers[3]. Recently, we have succeeded to control the QD height using the double-cap method in metalorganic chemical vapor deposition (MOCVD)[4], and observed single-photon emission from a single InAs QD[5]. A well-defined QD size and sharp interfaces between InAs and InP layers are a key factor to achieve better performance of a single-photon emitter at a certain wavelength. However, structures and interfacial properties of the QDs grown by the double-cap method have never been studied by techniques such as scanning tunneling microscopy (STM).

In this paper, we investigated interfacial properties of InAs/InP QDs grown by the double-capped method in MOCVD by means of cross-sectional STM (XSTM). Extremely sharp interfaces between the QD and the InP layer were observed, which indicates the formation of QDs with the discrete height in the range 6–14 monolayers (ML).

EXPERIMENT

The samples were grown on Sn-doped n-type InP(001) substrates in a low-pressure MOCVD using trimethylindium, arsine and phosphine as precursors. The sample consists of five periods of InAs QDs/InP structure. The details of the double cap method were described elsewhere[4]. Self-assembled QD layers were formed at 500 C by depositing 3.4 ML-InAs followed by 15-s-annealing in an AsH_3 ambient, and a 1.5-nm-thick InP layer was grown as a first cap layer. A 180-s-growth interruption with PH_3 exposure was performed to reduce the height of the QDs, and an 18-nm-thick InP layer was grown as a second cap layer.

XSTM was performed in an ultrahigh-vacuum chamber with a pressure of 2×10^{-8} Pa[6]. Samples were cleaved *in situ* to create clean and atomically flat (110) surfaces with exposed cross-section of InAs QDs. STM measurements were carried out in constant current mode at a sample bias voltage of −1.5 V and a tunnel current of about 50 pA.

RESULTS AND DISCUSSIONS

Figure 1(a) shows an XSTM image with a scan size of 62×11 nm^2. The brighter trapezoid with a height of 4.2 nm is identified as an InAs QD. The image shown in Fig. 1(b) is treated with a local mean equalization

CP893, *Physics of Semiconductors, 28th International Conference*
edited by W. Jantsch and F. Schäffler

filter, to enhance atomic details by removing the large scale background contrast due to the electronic structure and strain relaxation effects[7]. Superimposed stripes are attributed to atomic rows on the (110) surface. The trapezoidal shape of the InAs QD with the height of 14 ML and the lateral size of 45 nm is clearly observed in the XSTM image.

Focusing on one atomic layer on the (001) surface, we can obtain the fraction of As atoms in the atomic layer by calculating the sum of the length of the bright spots along the [110] direction in the image and dividing it by the total length of the atomic layer[8]. The brighter spot seen in the filled state image is identified as the surface As atoms in the InP layer, because the bond length of InAs is greater than that of InP and the valence band edge of InAs is higher than that of InP. The As compositional profile shown in Fig. 1(b) indicates that the InAs-on-InP interface is separated by 1 bilayer (2 ML) and the InP-on-InAs interface varies within 2 bilayer. The As composition inside the InAs QD is approximately unity, which indicates that the QD consists of pure InAs.

Figure 1(c) shows the XSTM image taken on a different area of the (110) cleaved surface. The bright line with the width of 1 bilayer, which is indicated by the arrows, is an InAs wetting layer. As shown in the composition profile, the wetting layer is not purely InAs, suggesting that a compositional alloying weakly takes place in the wetting layer.

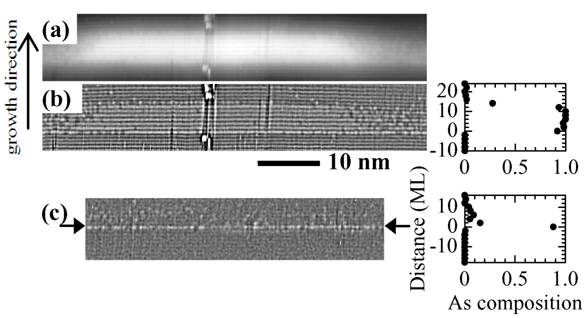

FIGURE 1. (a) Cross-sectional STM image of an InAs QD at a bias voltage of −1.5 V. (b) STM image treated by a local mean equalization filter. (c) Cross-sectional STM image of an InAs wetting layer at a bias voltage of −1.5 V. As-composition profiles along the growth direction are shown at the sides of the images.

We measured XSTM images on different areas of the surface to look for InAs QDs with different heights. Figure 2 (a) and (b) show the cross-sections of InAs QDs with the heights of 6 ML and 10 ML, respectively. The top and bottom interfaces of the dot are sharply separated from the InP layer, and there is no fluctuation of thickness in the dot. Therefore, we have found that the double-cap method in MOCVD can produce the well-defined dots with a monolayer-stepped height. Here, we note that the resolution of dot height in our study is 1 bilayer, because the As atom row on the (110) surface is observed in the filled state image.

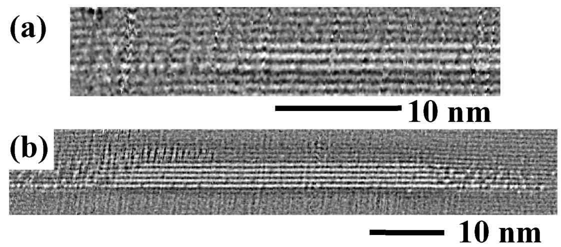

FIGURE 2. Cross-sectional STM images of InAs QDs with the heights of (a) 6 ML and (b) 10 ML, respectively.

Around the sides of the QDs shown in Fig. 1(b) and Fig 2(b), however, we notice that brighter spots are scattered about in the InP layer. As the brighter spot corresponds to the As atom distribution, this result suggests that the side walls of the QD are not sharp and the InAs QD is surrounded by the alloy layer in the lateral direction.

CONCLUSIONS

We have investigated interfacial properties and compositional distributions of InAs QDs grown by the double-cap method. XSTM images revealed that the top and bottom interfaces of InAs QD are extremely sharp, which confirmed the formation of QDs with a monolayer-stepped height by the double-cap method.

REFERENCES

1. C. Santori, D. Fattal, J. Vuckovic, G. S. Solomon and Y. Yamamoto, *Nature* **419**, 594 (2002).
2. Z. Yuan, B. E. Kardynal, R. M. Stevenson, A. J. Shields, C. J. Lobo, K. Cooper, N. S. Battie, D. A. Ritchie and M. Pepper, *Science*, **295**, 102 (2002).
3. C. Paranthoen, N. Bertru, O. Dehaese, A. L. Corre, S. Loualiche, B. Lambert and G. Patriarche, *Appl. Phys. Lett.* **78**, 1751 (2001).
4. Y. Sakuma, K. Takemoto, S. Hirose, T. Usuki, and N. Yokoyama, *Physica E* **26**, 81 (2005).
5. K. Takemoto, Y. Sakuma, S. Hirose, T. Usuki, N. Yokoyama, T. Miyazawa, M. Takatsu and Y. Arakawa, *Jpn. J. Appl. Phys.* **43**, L993 (2004).
6. I. Yamakawa, R. Oga, Y. Fujiwara, Y. Takeda and A. Nakamura: *Appl. Phys. Lett.* **84**, 4436 (2004).
7. Q. Gong, P. Offermans, R. Notzel, P. M. Koenraad, and J. H. Wolter, *Appl. Phys. Lett.* **85**, 5697 (2004).
8. I. Yamakawa, Y. Akanuma, B. S. Li, R. Akimoto and A. Nakamura, *Jpn. J. Appl. Phys.* **44**, L1337 (2005).