Localized formation of InAs quantum dots on shallow-patterned GaAs(100)

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Selective formation of InAs quantum dots on the sidewalls of mesa strips along both [01−1] and [011] directions of a GaAs(100) surface is demonstrated. This result is in sharp contrast to observations on traditionally deep-patterned substrates, where quantum dots are formed on top mesas and at bottom trenches. This distinction is explained kinetically and energetically. These results may encourage application of organized arrays of quantum dots. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2209157]

InAs quantum dots (QDs) on GaAs(100) by strain-driven self-assembly have emerged as a material with potential for optoelectronics and electronic devices.[1] One drawback to fabrication by self-assembly is that it yields InAs QDs that are distributed in a random manner on a flat GaAs(100) surface. As a result, one way to realize applications such as gain coupled distributed feedback QD lasers,[2] is to encourage the formation of InAs QDs into designed areas. With this benefit in mind, molecular-beam epitaxy (MBE) on prepatterned GaAs(100) substrates has recently been investigated as a technique to form InAs QDs in selected spatial locations.[2–6] Most previous studies have utilized relatively deeply etched patterns, on the order of a few hundreds of nanometers in height modulation,[2–4] to provide prepatterned surfaces for growth. In these cases, the InAs QDs were preferentially formed on the top edge and bottom trench, as illustrated in Fig. 1(a). In distinction from previous works, we report in this letter the localized formation of InAs QDs only along the sidewalls of shallow-patterned GaAs(100) surfaces, as comparatively illustrated in Fig. 1(b). Although the shallow-patterned approach has been used to achieve GaAs/AlGaAs sidewall quantum wires on GaAs(311)A, it has until now failed to realize the selective area formation of InGaAs QDs on GaAs(100).[5] While favorable formation of InAs QDs on faceted sidewalls was observed for deep-patterned substrates,[2] its origin was due to increasing the deposition along the sidewalls versus the top or bottom of the patterned strip—a very different mechanism from that described here.

In this work, samples were epitaxially grown by MBE on prepatterned GaAs(100) substrates with mesa strips of 1.5 μm wide and 35 nm tall along both [01−1] and [011] directions. The separation between strips is 2.5 μm. The patterns are formed by photolithography followed by wet etching. The patterned substrates were soldered with indium to a molybdenum block and degassed prior to loading into the MBE growth chamber. The surface oxide was desorbed at the substrate temperature of 610° C under a beam equivalent pressure (BEP) of 10 μTorr of As_4. Subsequently, a GaAs buffer layer was grown with the growth rate of 1.0 ML/s (monolayer per second). The resulting surface modulation depends on the thickness of the GaAs buffer layer, which plays an important role in determining the selective area formation of InAs QDs, as demonstrated below. After the GaAs growth, the substrates were cooled to 535° C for InAs deposition. The nominal growth rate of InAs was 0.013 ML, as determined by *in situ* reflection high energy electron diffraction (RHEED). The RHEED pattern became spotty after the deposition of the 1.5 ML, indicating the nucleation of self-assembled InAs QDs due to strain relaxation.

Figures 2 and 3 show the atomic force microscope (AFM) images of 1.6 ML InAs QDs grown on 500 nm buffered GaAs surfaces with mesa strips along [01−1] and [011], respectively. The initial mesa strips are the same along both directions but remarkably different after growth of the GaAs buffer as the result of the high surface anisotropy of both atom diffusion and incorporation.[7] Based on the measurements of line profiles, the height and width of the mesa strips along [01−1] are nearly constant, although the top portion of the strips is more rounded. Meanwhile, the sidewalls of the mesa strips are profiled as vicinal GaAs(100) surfaces with a misorentation of about 3.0°. In comparison, the mesa strips along [011] grow to have a width of more than 2.0 μm, and the height has been decreased about 5.0 nm. The profile of these sidewalls is characterized as vicinal GaAs(100) surface with a misorientation of about 1.5°. For both strip directions, the selective area of InAs QD formation is observed to be distributed on the sidewalls, either along [01−1] or [011]. Only a few InAs QDs are trapped at the bottom trench or on the mesa top due to the natural roughness of GaAs(100). For

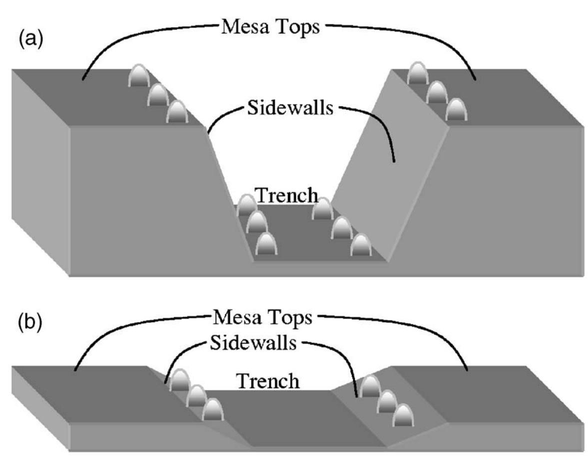

FIG. 1. Schematic illustrations of selective formation of self-assembled InAs QDs on GaAs(100) substrates, deep patterned (a) and shallow patterned (b), respectively.

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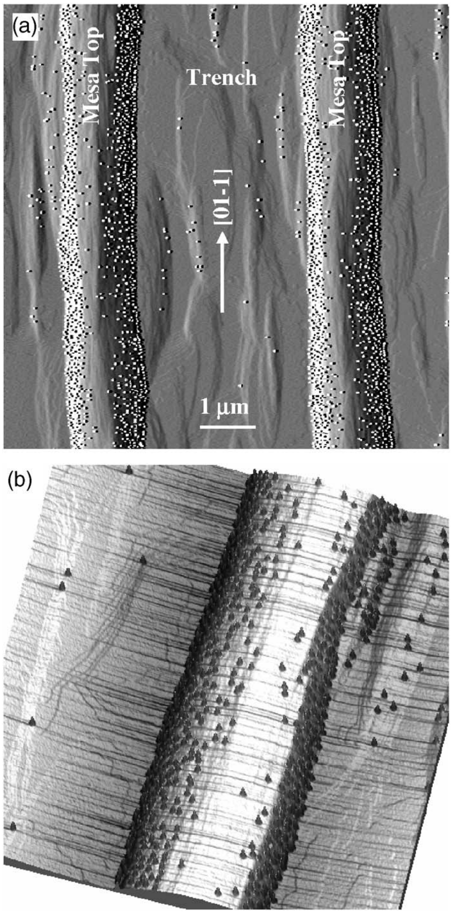

FIG. 2. AFM images of 1.6 ML InAs QDs grown on 500 nm buffered GaAs surfaces with mesa strips along [01−1].

example, the moundlike surfaces shown in the trench of Fig. 2(a) which are a few hundreds of nanometers wide and a few micrometers long (typical for GaAs MBE growth[8,9]) act as trapping centers for a few InAs QDs. The size of InAs QDs grown on the patterned substrate is about 50 nm in lateral diameter and 13 nm in height is similar to what is expected on a flat GaAs(100) surface.

The preferential growth of QDs along the strip sidewalls is a robust result. For example, Fig. 4 shows a typical AFM image of 1.8 ML InAs QDs grown on 1.0 μm buffered GaAs(100) with mesa strips along [011]. The mesa strips along [011] are shown to spread laterally along the surface. As a result, the bottom trenches disappeared and sidewalls of neighboring mesa strips intersect each other. The preferable formation of InAs QDs on the sidewalls persists, although with a very different pattern of QDs as the result of the different arrangement of the sidewalls. Therefore, starting with the same prepatterned mesa structure, we can engineer the InAs QD formation into different areas by controlling the final surface morphology through the growth of the GaAs buffer layer and perhaps other growth parameters as well. Moreover, the final surface profile on shallow-patterned GaAs substrates is potentially predictable based on theoretical simulation of MBE growth.[10]

As demonstrated in this work, the sidewalls of *shallow-patterned* GaAs(100) substrates are most favorable sites for the formation of InAs QDs. However, as already noted, it has been reported that the edges of mesa tops and bottom trenches of *deep-patterned* GaAs(100) substrates are prefer-

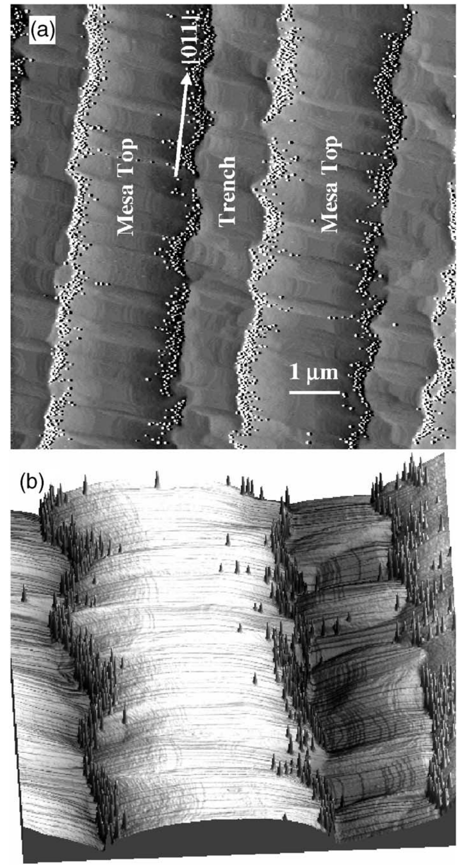

FIG. 3. AFM images of 1.6 ML InAs QDs grown on 500 nm buffered GaAs surfaces with mesa strips along [011].

able sites for the growth of InAs QDs.[2–4] How does the amplitude of surface features make such a primary distinction? Based on simple consideration of both kinetic and energetic mechanisms, the favorable sites for strained InAs QDs can be anywhere on patterned GaAs substrates.[11] However, for deep-patterned substrates, the amplitude of the surface modulation is enough for the surface slopes to reach some low energy facets such as {311}/{411} and {111}.[2–4] Generally, such faceted sidewalls have a lower InAs growth rate due to In migration away and partly due to a lower In flux. As a result, the edges of mesa tops and bottom trenches of

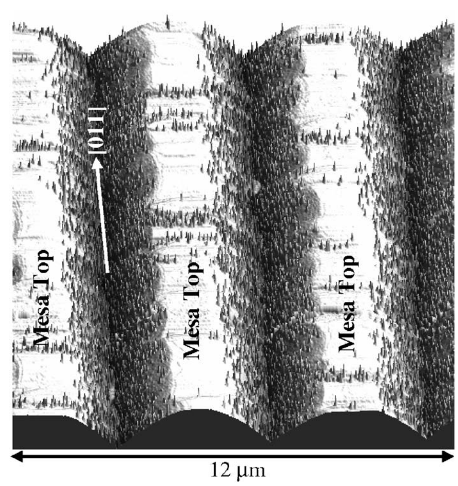

FIG. 4. AFM images of 1.8 ML InAs QDs grown on 1.0 μm buffered GaAs surfaces with mesa strips along [011].

deep patterns have a higher InAs growth rate and therefore the preferable formation of InAs QDs is expected. In fact, the mechanism of InAs strain relaxation on non-(100) faceted sidewalls can be very different from (100) faceted sidewalls. This further complicates the picture of QD growth behavior on deep-patterned GaAs(100) substrates but is still consistent with the lack of QD formation on its sidewalls. For example, InAs growth on GaAs(110) and (111) has been observed to maintain its two-dimensional mode without QD formation.[12,13]

For shallow-patterned substrates as reported in this letter, the sidewall slopes are only 1°–3°, far from any low energy facet. The shallow sidewall can be described as vicinal GaAs(100) surfaces, which are characterized with high density of monolayer steps.[14] The monolayer steps would be favorable for InAs QDs in terms of both kinetics and energetics. The monolayer steps are expected to act as kinetic barriers for In surface migration and therefore trap In atoms around. Moreover, the edge of monolayer steps is the energetic favorable site for InAs strain relaxation and therefore InAs QDs tend to form around.[15] As a result, the sidewalls formed from shallow-patterned substrates, characterized by high density of monolayer steps, become the most favorable sites for the formation of InAs QDs.

In retrospect, the formation of InAs QDs near the edges of mesa tops and near the edges of the trenches of the deep-patterned substrates[2–4] is consistent with the favorable formation of QDs in high-step-density regions as well. The mesa tops and the trenches, as well as the sidewalls of the deep-patterned substrates have different facets. The edges of mesa tops and the edges of the trenches are the transition areas where the surface goes from one facet to another, not singular but filled with steps.

The preferable formation of InAs QDs on bunched step regions has been reported on vicinal GaAs(100) surfaces by metal organic chemical vapor deposition.[16] The difference in our case is that the bunched step regions are positioned by shallow strips through lithography. The approach of spatially positioning QDs into microscale patterns formed by traditional lithography may further encourage the application of InAs nanoscale structures.[17]

In summary, we have used shallow-patterned GaAs(100) substrates to position InAs QDs into specific regions. The InAs QDs are preferably formed on the sidewalls of shallow strips as opposed to the edge of mesa tops and bottom trenches as observed on deep-patterned structures. This distinction is explained kinetically and energetically based on the fact that the sidewalls of shallow surface features are characterized by high density of monolayer steps and the sidewalls of deep surface features are faceted with low energy index.

[1] D. Bimberg, M. Grundmann, and N. N. Ledentsov, *Quantum Dot Heterostructures* (Wiley, New York, 1998), and references therein.
[2] D. S. L. Mui, D. Leonard, L. A. Coldren, and P. M. Petroff, Appl. Phys. Lett. **66**, 1620 (1995).
[3] G. S. Solomon, Z. Xie, W. Fang, J. Y. Xu, A. Yamilov, H. Cao, Y. Ma, and S. T. Ho, Phys. Status Solidi B **238**, 309 (2003).
[4] A. Konkar, R. Heitz, T. R. Ramachandran, P. Chen, and A. Madhukar, J. Vac. Sci. Technol. B **16**, 1334 (1998).
[5] Q. Gong, R. Nötzel, H.-P. Schönherr, and K. H. Ploog, Physica E (Amsterdam) **13**, 1176 (2002), and references therein.
[6] H. Z. Song, T. Usuki, T. Ohshima, Y. Sakuma, M. Kawabe, Y. Okada, K. Takemoto, T. Miyazawa, S. Hirose, Y. Nakata, M. Takatsu, and N. Yokoyama, Nanoscale Research Letterss **1**, 110601 (2005).
[7] E. J. Heller, Z. Y. Zhang, and M. G. Lagally, Phys. Rev. Lett. **71**, 743 (1993).
[8] M. D. Johnson, C. Orme, A. W. Hunt, D. Graff, J. Sudijono, L. M. Sander, and B. G. Orr, Phys. Rev. Lett. **72**, 116 (1994).
[9] A. Ballestad, B. J. Ruck, M. Adamcyk, T. Pinnington, and T. Tiedje, Phys. Rev. Lett. **86**, 2377 (2001).
[10] A. Ballestad, T. Tiedje, J. Schmid, B. Ruck, and M. Adamcyk, J. Cryst. Growth **271**, 13 (2004).
[11] R. V. Kukta and D. Kouria, J. Appl. Phys. **97**, 033527 (2005).
[12] H. Yamaguchi, M. R. Fahy, and B. A. Joyce, Appl. Phys. Lett. **69**, 776 (1996).
[13] H. Wen, Zh. M. Wang, J. L. Shultz, B. L. Liang, and G. J. Salamo, Phys. Rev. B **70**, 205307 (2004).
[14] Z. M. Wang, J. L. Shultz, and G. J. Salamo, Appl. Phys. Lett. **83**, 1749 (2003), and references therein.
[15] S. O. Cho, Zh. M. Wang, and G. J. Salamo, Appl. Phys. Lett. **86**, 113106 (2005).
[16] M. Kitamura, M. Nishioka, J. Oshinowo, and Y. Arakawa, Appl. Phys. Lett. **66**, 3663 (1995).
[17] S. S. Li, G. L. Long, F. S. Bai, S. L. Feng, and H. Z. Zheng, Proc. Natl. Acad. Sci. U.S.A. **98**, 11847 (2001).