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Fabrication of single- or double-row aligned self-assembled quantum dots by utilizing SiO₂-patterned vicinal (001) GaAs substrates

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We investigated the formation of In₀.₈Ga₀.₂As self-assembled quantum dots (SAQDs) grown on SiO₂-patterned 1°, 2°, and 5°-off (001) GaAs substrates by selective area metalorganic vapor phase epitaxy technique. The SiO₂ patterns were filled with various stripe opening windows along the misorientation direction of the substrates. During the growth of the GaAs buffer layer on the opening regions, the steps on the (001) top facet was affected by the widths of the (001) top facet and the misorientation angles of the substrates. Single- or double-row aligned In₀.₈Ga₀.₂As SAQDs having definite interval were successfully fabricated on the (001) top facet with optimized top width and periodicity of step bunching. These results indicate that the selective growth technique of SAQDs by utilizing SiO₂-patterned vicinal substrates is promising for nanoelectronic device applications such as single-electron memory devices. © 2002 American Institute of Physics.

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were 2.5 × 10^{-5}, 5.0 × 10^{-7}, and 9.1 × 10^{-7} atm, respectively. The growth temperature for the GaAs and In_{0.8}Ga_{0.2}As SAQDs were 700 and 500 °C, and the corresponding nominal thickness were 200 nm and 3.2 ML, respectively.

Figures 1(a) and 1(b) show SEM images of In_{0.8}Ga_{0.2}As SAQDs and GaAs buffer layers grown on SiO_{2}-patterned 1°-off (001) GaAs substrate with \( W_0 \) of 560 and 620 nm, respectively. During the growth of the GaAs buffer layer on opening region of SiO_{2}-patterned vicinal (001) GaAs substrates, the formations of GaAs buffer layers have been changed to mesa-structure which consist of (001) top facet, \{113\} A facets surrounding the the top region, and \{111\}A facets on side walls. As the growth of GaAs buffer layer proceeds on opening regions, the widths of the (001) top facet \( W_{(001)} \) were directly proportional to \( W_0 \) and the corresponding \( W_{(001)} \) were 80 and 153 nm, respectively. In_{0.8}Ga_{0.2}As SAQDs were not formed on \{111\}A and \{113\}A facet, and grew selectively on (001) top facet. As shown in Figs. 1(a) and 1(b), the formations of In_{0.8}Ga_{0.2}As SAQDs were changed by \( W_{(001)} \). The number of SAQDs perpendicular to the [110] misorientation direction on (001) top facet was increased by the enhanced \( W_{(001)} \). The interval of SAQDs along the [110] misorientation direction on (001) top facet \( d_i \) was not clear in Fig. 1(a), whereas it was clearly distinguished in Fig. 1(b). Also, the average \( d_i \) as a function of \( W_{(001)} \) in Fig. 1(a) was narrower than in Fig. 1(b). Figure 1(c) shows an AFM image of In_{0.8}Ga_{0.2}As SAQDs grown on unpatterned 1°-off (001) GaAs substrate with the same growth conditions of GaAs buffer layer and SAQDs. SAQDs were formed on step lines transformed by bunching effect of GaAs buffer layer due to the surface migration length of Ga adatoms along the [110] misorientation direction of the substrate \( (L_i) \). The interval of step lines was 67 nm and it was in accordance with \( d_i \) in Fig. 1(b). Therefore, it can be confirmed that \( L_i \) on the (001) top facet in Fig. 1(b) is in accordance with that in Fig. 1(c), whereas \( L_i \) on the (001) top facet in Fig. 1(a) is smaller than that in Fig. 1(c). There is no clear explanation about the reason yet, but we believe this may be caused by the dissimilar inter-facet migration of Ga adatoms on different facets, when \( W_{(001)} \) is changed.\(^{11}\)

Figures 2(a), 2(b), and 2(c) show SEM images of In_{0.8}Ga_{0.2}As SAQDs and GaAs buffer layers grown on SiO_{2}-patterned 2°-off (001) GaAs substrate with \( W_0 \) of 547 and 560 nm, and an AFM image of In_{0.8}Ga_{0.2}As SAQDs grown on unpatterned 2°-off (001) GaAs substrate, respectively. The corresponding \( W_{(001)} \) in Figs. 2(a) and 2(b) were 43 and 52 nm, respectively. \( d_i \) in Fig. 2(b) and the interval of step lines in Fig. 2(c) have the same width of 52 nm. \( d_i \) in Fig. 2(a) was narrower than that in Fig. 2(b). Therefore, the relation between the formation of SAQDs and \( W_{(001)} \) was similar to that on SiO_{2}-patterned 1°-off (001) GaAs substrate. However, \( W_{(001)} \) having definite \( d_i \) for 2°-off (001) GaAs substrate [in Fig. 2(b)] was narrower than that for 1°-off GaAs substrate [in Fig. 1(b)].

Figure 3 shows the experimental results for \( d_i \) as a function of \( W_{(001)} \). The filled triangles and open circles represent the experimental results for \( d_i \) of In_{0.8}Ga_{0.2}As SAQDs grown on SiO_{2}-patterned 1°-off and 2°-off (001) GaAs substrates, respectively. The enhanced \( d_i \) was caused by the enhanced \( W_{(001)} \), so that it saturated to the same width as interval of step lines on unpatterned vicinal substrates. We found that large fluctuation in \( d_i \) value occurred up to a certain value of \( W_{(001)} \), after which \( d_i \) value saturated. This fluctuation region of \( d_i \) for 1°-off substrate (~150 nm) (I) is wider than that for 2°-off substrate (~50 nm) (II) as shown in Fig. 3. For quantitative understanding, we fit the experimental results in the following equation:

\[
W_{(001)}(\text{nm}) = \begin{cases} 
150 & \text{for } 1°-\text{off GaAs} \\
50 & \text{for } 2°-\text{off GaAs}
\end{cases}
\]
according to the experimental results, the value of \( d_{\parallel} \) for the substrates are changed. The facet migration of Ga adatoms on different facets, when the misorientation angles of the substrates were reduced, as the misorientation of substrates was larger. There is no clear explanation yet about the relation between the misorientation angles of the substrate and \( d_{\parallel} \), but we also believe this to be caused by the dissimilar interfacet migration of Ga adatoms on different facets, when the misorientation angles of the substrates are changed.

In order to reduce the fluctuation regions for \( d_{\parallel} \) which are undesirable for electronic device applications, we applied the same growth condition to SiO\(_2\)-patterned 5°-off (001) GaAs substrate. Figures 4(a) and 4(b) show SEM images of In\(_{0.8}\)Ga\(_{0.2}\)As SAQDs grown on SiO\(_2\)-patterned 5°-off (001) GaAs substrate with \( W_0 \) of 628, and 650 nm, respectively. The corresponding \( W_{(001)} \) were 19 and 46 nm, respectively. Single-row aligned SAQDs in Fig. 4(a) and double-row aligned SAQDs in Fig. 4(b) have the same \( d_{\parallel} \) of 50 nm and the fluctuation region for \( d_{\parallel} \) was not observed. Therefore, single- or double-row aligned SAQDs having definite \( d_{\parallel} \) was successfully fabricated by utilizing SiO\(_2\)-patterned 5°-off (001) GaAs substrate and a reduction of the fluctuation region for large misorientation angle was confirmed.

In summary, the interval of In\(_{0.8}\)Ga\(_{0.2}\)As SAQDs grown on SiO\(_2\)-patterned vicinal GaAs (001) substrates by SA-MOVPE can be controlled by \( W_{(001)} \) and the misorientation angle of the substrate. In order to maintain definite \( d_{\parallel} \) on (001) top facet equal to the interval of step lines on unpatterned vicinal (001) GaAs substrate, it is effective to use vicinal substrate having higher misorientation angles, single- or double-row aligned SAQDs having definite \( d_{\parallel} \) were successfully fabricated by utilizing 5°-off (001) GaAs substrate. These results suggest that the selective growth technique of SAQDs by utilizing SiO\(_2\)-patterned vicinal substrates is promising for nanoelectronic device applications, such as single-electron memory devices.

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