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Vicinal surface as a tool for QD control: InAs on GaAs

V. P. Evtikhiev
Ioffe Physico-Technical Institute, St Petersburg, Russia

1 Introduction

One of the most promising methods for the preparing of uniform QDs array is the molecular beam epitaxy (MBE) in Stranski–Krastanow growth mode [1]. Many investigations of InAs QDs show that their density and size depends on the growth conditions and QDs arrays in the density range of 10^8-10^{11} cm^{-2} may be received [2, 3]. The formation of InAs QD arrays with a density greater than 3×10^{10} cm^{-2} on a correctly oriented GaAs(001) surface is accompanied, as a rule, by coalescence of a noticeable number of QD into large islands, which leads to a radical broadening of the QD size distribution [3]. So, the independent control of sizes and density of QDs is one of the main problems for the creation QD heterostructures suitable for the devices application.

For the creation of dense arrays of uniform QDs we suggest to use the conventional MBE growth in Stranski–Krastanov growth mode on the vicinal GaAs(001) substrate misoriented to the [010] direction. On such vicinal surfaces there appears a net of small terraces, separated by steps from all the sides. The Schwoebel potential barrier at the step edges may considerably suppress the surface diffusion of adatoms between the terraces [4], and the QDs growth on each terrace will occur primarily from the material deposited on the same terrace.

2 Theory

We have performed Monte-Carlo simulation of the terraces formation on the vicinal GaAs(001) surfaces misoriented to the [010] direction. We took into account the processes of the atom adsorption and desorption on the surface, adatom migration, adatom attachment and detachment to the step. The elemental detachment processes for a different kind of steps configuration are shown in the Fig. 1(a). A Monte-Carlo simulation of the GaAs growth shows that the processes $n3$, $n4$ and $n7$ dominate over the other elemental detachment processes ($n1-n10$). The shape of the terraces depends strongly on the variation of the atom detachment activation energies (E_{nx}). The activation energy ratio E_{n3}/E_{n4} controls the ordering of the waves. Parameter E_{n7} controls the abruptness of the wave. With the decreasing of E_{n7} value, terraces become wave-shaped and connected by the gates (see Fig. 1(b)).

In order to reveal the possible role of adatom diffusion between the connected terraces, we estimate the coalescence rate of the QDs located on the neighboring terraces. We simulated the motion of the adatoms by the Monte-Carlo method and determined the number of adatoms which began to move on the edge of one QD and reached the edge of a neighboring QD per unit time. The simulation show that increasing the constriction linearly retards coalescence rate.

3 Technological approach

Experimentally the role of substrate misorientation on the QDs formation was investigated by atomic force microscopy, photoluminescence and electroluminescence. The heterostruc-

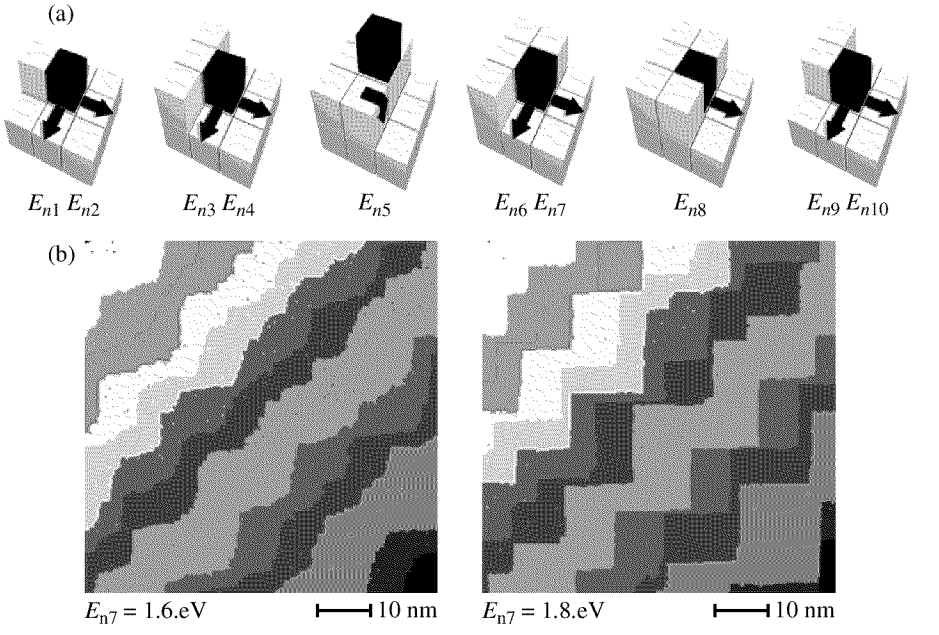

Fig. 1. The elemental detachment processes and results of Monte-Carlo simulation of the GaAs growth on misoriented substrate.

tures for all kinds of measurements were grown in identical growth conditions. Each growth process include two stages. The first stage is the preparation of terraces net during GaAs growth in step flow growth mode and the second—the growth of InAs QDs in Stransky–Krastanow growth mode. The effective thickness of InAs covering was 3 monolayers. Each epitaxy process was performed simultaneously on GaAs(001) surfaces misoriented to the [010] direction by 0, 1, 2, 4, and 6°. The comparatively small range of variation of the misorientation angles was chosen so that the surfaces would differ from one another only in growth-step density without qualitative variation in the surface morphology caused by the approach to new singular faces.

4 Results and discussion

Studying the surface structure of GaAs samples by AFM, we have revealed on the vicinal surfaces the net of wave-like terraces joined by gates as has been predicted by the Monte-Carlo simulation (Fig. 2, upper row). Increasing of the misorientation angle leads to an increase in the density of the terraces and decrease in their mean width from 500 Å for 1° to 250 Å for 6°. These values are considerably larger than the dimensions of the terraces calculated under assumption that the step height is one monolayer. The observed difference is explained by the phenomenon of step-bunching, which in our case increases with increasing of the misorientation angle from 2–3 ML for 1° to roughly 10 ML for 6°.

At InAs coverage of 3 ML (Fig. 2, down row), InAs QDs arrays were found on the terraced surfaces. Also present on the surfaces are large InAs islands formed as a result of the coalescence of InAs QDs. Their number falls dramatically with increase of the misorientation angle and on the surface with 6° misorientation there are scarcely any large InAs islands. Increasing of the terrace density with the misorientation angle leads to the

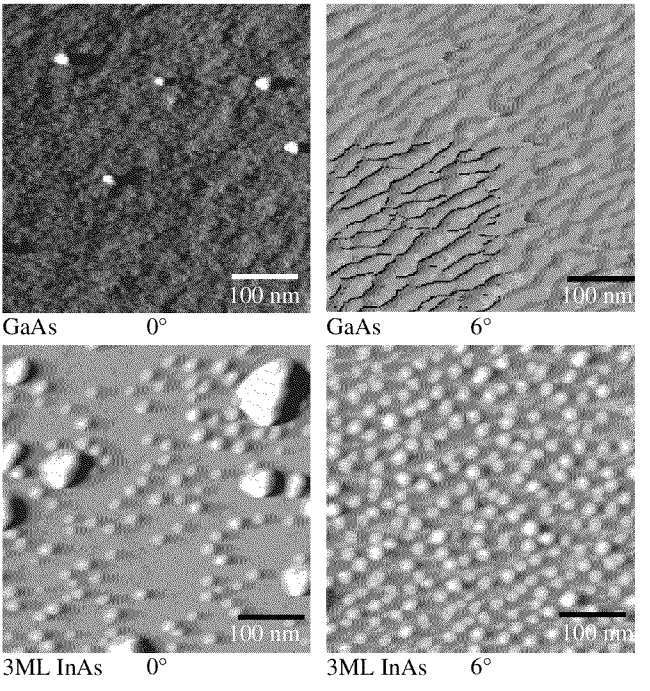

Fig. 2. AFM image of GaAs surfaces (upper row) and InAs QDs (3 ML InAs coverage thickness) (down row) MBE grown on the GaAs(001) surfaces exactly oriented and misoriented by 6° to the [010] directions.

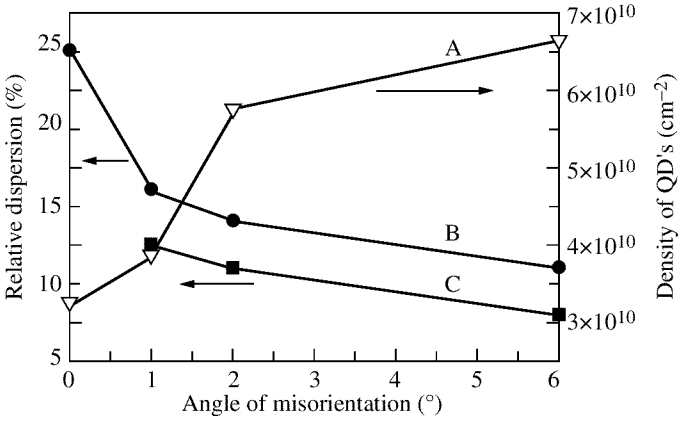

Fig. 3. The relative dispersion of distributions of InAs QD's height (B) and terraces (C) width (left scale) and density of QDs (A) (right scale) as a function of the angle of misorientation.

higher density of QDs (Fig. 3), decreasing of their mean height from 34 Å for 0° to 20 Å for 6° and to the more uniform size distribution.

The similar character of variation of the spread in QDs height and in terraces width with surface misorientation let us conclude that QDs size dispersion is controlled by the terraces areas distribution.

For PL study we prepare two sets of samples. They differ only by the interruption time

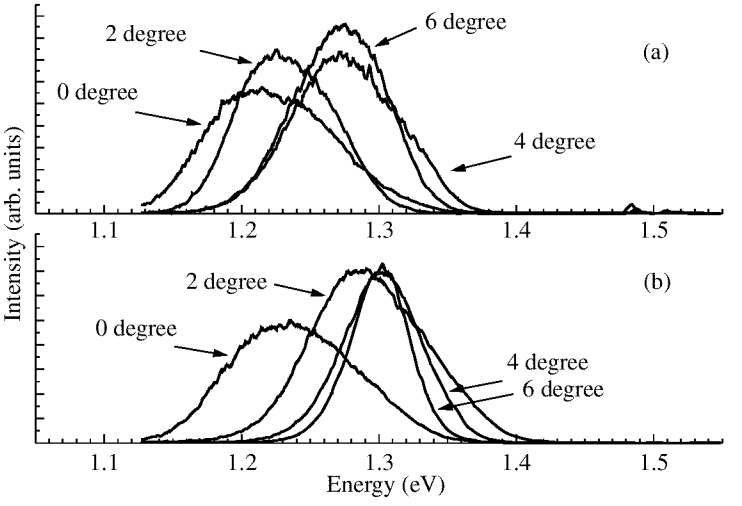

Fig. 4. The PL spectra recorded at $T = 77$ K for the samples with the growth interruption time $t_{\text{int}} = 15$ min (a) and $t_{\text{int}} = 10$ s (b).

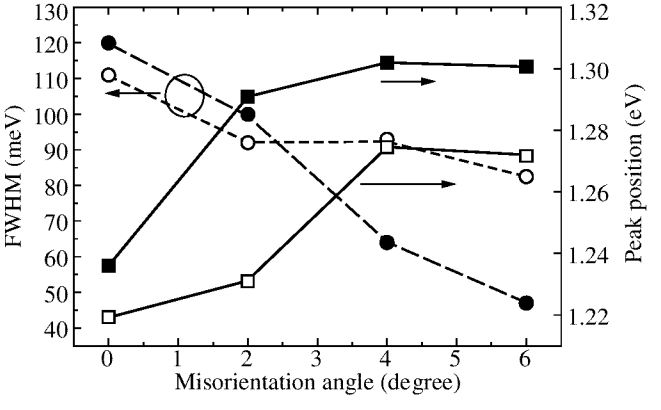

Fig. 5. The maximum position (squares) and the FWHM (triangles) of the PL line for the samples with the growth interruption time $t_{\text{int}} = 15$ min (solid) and $t_{\text{int}} = 10$ s (open).

(t_{int}) between the end of QDs growth and start of the GaAs layer overgrowth. For the first set $t_{\text{int}} = 15$ min and for the second one $t_{\text{int}} = 10$ s. In the grown heterostructures the InAs QDs single sheet array was confined by GaAs barriers (200 Å) which were surrounded by the AlAs/GaAs superlatticies and cladding $Al_{0.7}Ga_{0.3}As$ layers. The PL spectra ($T = 77$ K, $\lambda = 514.5$ nm, $P = 200$ A/cm^2) for both the series of samples are presented in the Fig. 4(a) and Fig. 4(b). The position of the PL line maximum and the full width on the height middle (FWHM) of the PL lines versus angle of misorientation are shown in the Fig. 5. For both the series of spectra the misorientation of the substrate leads to blue shift of the maximum and decrease of the FWHM of PL lines. These effects can be naturally explained by the decrease of the sizes and better size uniformity for the InAs QDs on the misoriented surfaces what was revealed by AFM study for the open QDs arrays. The observed effects depend on the growth interruption time t_{int} and are less pronounced in the samples grown with longer t_{int}.

It is natural to connect the dependence of the InAs QDs sizes on the interruption time with the probability of adatom surface migration. On the misoriented surfaces patterned with the dense net of terraces, adatom surface diffusion between terraces should be much slower then on exactly oriented surface, since adatom migration between terraces occurs mainly through the gateways connecting terraces. The increase of the misorientation angle makes terraces and gates smaller and causes progressive suppression of the adatom migration. The effect of interruption time on the PL spectra should be small for exactly oriented surfaces with fast adatom migration and became stronger on the misoriented surfaces. However, with the further increase of the misorientation angle it again may become weaker, when migration will completely supressed on the time scale of chosen t_{int}. The comparison of the data in Fig. 4 shows that in our studies effect of the growth interruption time is stronger for sample with 2 degree misorientation. So, we imply that QDs formation on the misoriented surface comprise two main stages with different characteristic times. First process is very quick. The self-assembled QDs array with high density and high uniformity appear on this stage. On the second, much longer stage QDs increase in sizes due to QDs interactions. This interaction occurs via surface migration of adatoms between QDs. The changes in the QDs morphology on this second growth stage determine variations in the position and width of the QDs PL lines for samples grown with longer interruption time. The misorientation creates a new, much slower time scale for this stage of the QDs formation because of the suppression of the adatom migration between terraces.

We successfully used such substrates for the fabrication of laser heterostructures with a single sheet QDs array. The electroluminescence spectra exhibits the same main features that were observed in PL measurements. As it was predicted by theory [5] the threshold current of the "classical" single sheet QD laser, prepared on these heterostructures shows very strong dependency versus their FWHM. The lowest threshold current density (210 A/cm^2) exhibits the broad area (100 μm) lasers with high reflecting mirror coating made from 4 degree misoriented substrate.

5 Conclusion

We have found that the application of GaAs(001) substrates misoriented to the [010] direction in conventional MBE growth gives an effective tool for the independent control of InAs QDs density and size, permits to improve the QDs sizes dispersion. This possibility originates from special surface patterning which appear on misoriented substrates and may be used in the MBE growth of different types of QDs.

References

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