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# Effect of GaAs (001) surface misorientation on the emission from MBE grown InAs quantum dots

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**Abstract.** The photoluminescence (PL) is used to study the capped InAs QDs single sheet array MBE grown on the vicinal GaAs (001) surfaces misoriented to the [010] direction by 0, 2, 4, 6 degree. The misorientation leads to the blue shift and the narrowing of InAs QDs PL lines and makes PL efficiency higher. These effects are related, respectively, with the smaller size and higher size uniformity of the InAs QDs and reduction of the number of large InAs islands on the misoriented surfaces. It was found that decrease of the growth interruption time between the end of QDs growth and start of the GaAs layer overgrowth makes these modifications of the PL spectra with surface misorientation stronger and efficiency of the PL higher.
With the use of misoriented substrates, single sheet QDs laser with threshold current density of 210 A/cm$^2$ at room temperature was realized.

## Introduction

Self-assembled quantum dots (QDs) arrays attract much attention due to the interest in their potential device applications [1-2]. However, to realize the high performance optical devices based upon QDs it is necessary to win the high size uniformity and high internal quantum efficiency of the QDs. Our preliminary AFM studies on the open InAs QDs arrays [3] have shown that it is possible to improve homogeneity and reach higher density of QDs growing them on the vicinal GaAs (001) surfaces misoriented to the [010] direction. This possibility originates from a specific patterning of the surfaces misoriented to the [010] direction. On such misoriented surfaces there appear multiatomic steps going to the [110] and [$\bar{1}$10] directions.

In that work we studied the photoluminescence (PL) of the capped InAs QDs single sheet array MBE grown on the vicinal GaAs (001) surfaces misoriented to the [010] direction.

## 1 Experimental procedure

The two sets of samples were grown by molecular beam epitaxy (MBE) in Stransky–Krastanow growth mode. Each set of samples consists of four samples, which were prepared via simultaneous InAs QDs single sheet array growth on four GaAs substrates misoriented by 0, 2, 4 and 6 degrees to the [010] direction. Two sets of samples differ only by the interruption time ($T_{int}$) between the end of QDs growth and start of the GaAs layer overgrowth. For the first set $T_{int}$ = 15 min and for the second one $T_{int}$ = 10 s. The thickness of the InAs deposition was 2.9 ML. The growth temperature of InAs QDs was 470°C and the III–V elements flux ratio was equal 2. 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.

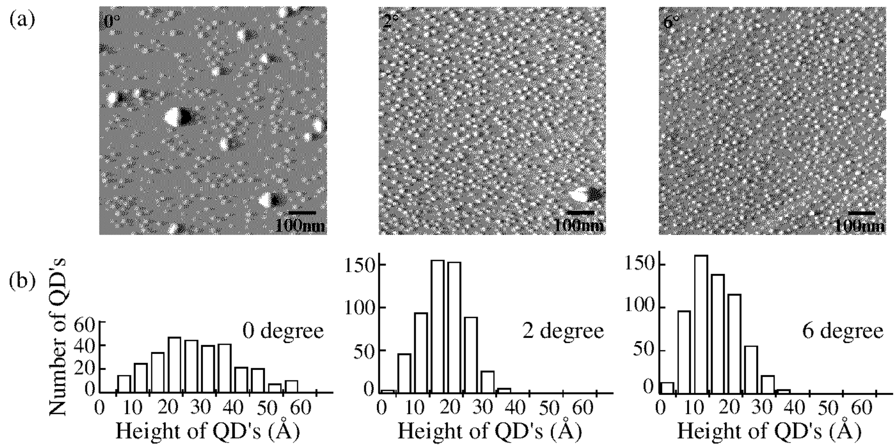


**Fig. 1.** (a) AFM images of the open InAs QDs arrays on the GaAs surfaces misoriented to the [010] direction by 0, 2 and 6 degrees. (b) the dependence of the InAs QDs height distributions on the angle of misorientation.

## 2 Results and discussions

In the Fig. 1(a) we show atomic force microscopy (AFM) images of the open InAs QDs arrays on the GaAs surfaces misoriented to the [010] direction by 0, 2 and 6 degrees. Fig. 1(b) presents the dependence of the InAs QDs height distributions on the angle of misorientation. It is clearly seen that misorientation of the GaAs substrate already on small angles results in the reduction of the number of large InAs islands on the surface and leads to higher density and better size uniformity of InAs QDs. Simultaneously, QDs become smaller.

In the Fig. 2 we present the PL spectra for capped InAs QDs. 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. 3. 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 for the open QDs arrays in Fig. 1. It is important to note that the observed effects depend on the growth interruption time Tint and are less pronounced in the samples for which $T_{int}$ was longer. The last observation directly demonstrates an importance of the kinetic processes on the surface in the formation of the InAs QDs.

Let us remind that on the exactly oriented GaAs(001) surface adatom diffusion at the chosen growth conditions is fast. At the same time on the misoriented surfaces patterned with the dense net of terraces, adatom surface diffusion between terraces should be much slower, since adatom migration between terraces occurs mainly through the gateways connecting terraces [4]. The increase of the misorientation angle makes terraces and gates smaller and causes progressive suppression of the adatom migration. In this connection, the effect of interruption time on the PL spectra should be small for exactly oriented surfaces and became stronger on the misoriented surfaces. However, with the further increase of the misorientation angle it again should become weaker. This behaviour has been found experimentally. The comparison of the data in Fig. 3 shows that effect of the growth interruption time is stronger for sample with 2 degree misorientation.

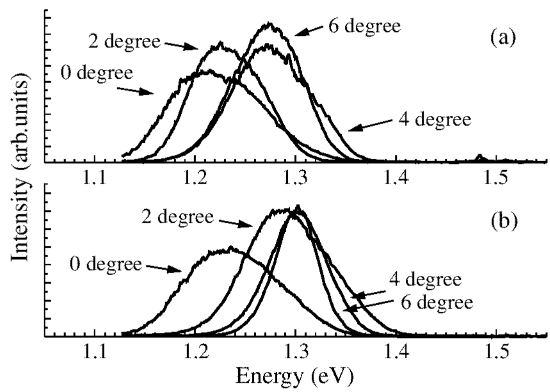


**Fig. 2.** The PL spectra recorded at $T = 77$ K for the samples with the growth interruption time $T_{\mathrm{int}} = 15$ min (a) and $T_{\mathrm{int}} = 10$ s (b).

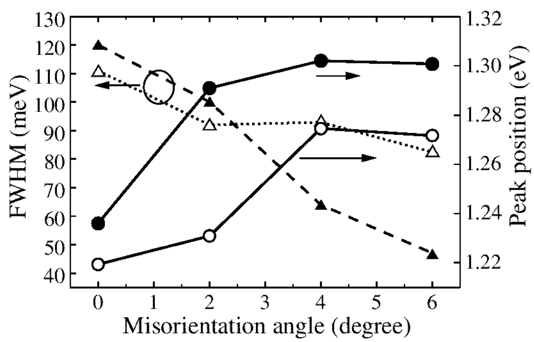


**Fig. 3.** The position of the PL line maximum (full circles for the samples with the growth interruption time $T_{\mathrm{int}} = 15$ min, open circles for $T_{\mathrm{int}} = 10$ s) and FWHM of the PL line (full triangles for the samples with the growth interruption time $T_{\mathrm{int}} = 15$ min, open triangles for $T_{\mathrm{int}} = 10$ s).

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. So, 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 on the misoriented surfaces.

The suppression of the adatom migration on the misoriented surfaces also allows essentially decrease the density of the large InAs islands. These large islands contain dislocations and usually are considered as efficient centres of nonradiative recombination.

The application of the GaAs(001) substrates misoriented to the [010] direction permits to win the better uniformity and higher density of QDs arrays with high internal quantum efficiency. We successfully used such substrates for the fabrication of laser heterostructures with a single sheet QDs array. Obtained for such laser structures good internal quantum efficiency and FWHM values of 40 meV permitted to realise classical QDs laser with low threshold current density [5]. The broad area (100 $\mu$m) lasers with high reflecting mirror

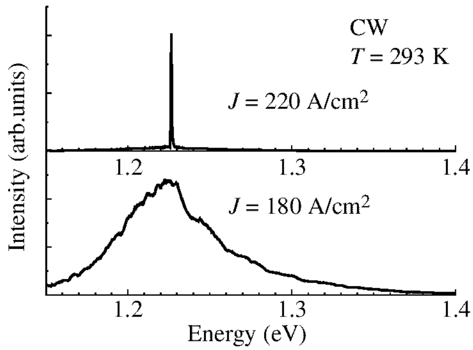


**Fig. 4.** The electroluminescence and lasing spectra for the broad area (100 $\mu$m) lasers with high reflecting mirror coating mode from 4 degree misoriented substrate.

coating made from 4 degree misoriented substrate show the threshold current density of 210 A/cm$^2$ at room temperature. The electroluminescence and lasing spectra of such laser are presented in Fig. 4.

## 3 Conclusion

We have found that misorientation of GaAs(001) substrates to the [010] direction leads to the blue shift and the narrowing of the InAs QDs PL lines. The observed effects are related with the decrease of sizes and better size uniformity of the InAs QDs grown on such substrates. The modifications in the InAs QDs morphology arise due to the suppression of the adatom diffusion on the misoriented GaAs surface and become stronger with the increase of misorientation angle and the decrease of the MBE growth interruption time $T_{\rm int}$. The substrate misorientation gives also a new, much slower, time scale for the QDs redistribution by sizes and makes weaker the QDs coalescence process. High quantum efficiency can be reached for QDs grown on the misoriented substrates.

We successfully used the MBE growth of the InAs QDs on the GaAs (001) substrates misoriented to the [010] direction for fabrication of classical QDs laser diodes. The low threshold current densities were achieved for the broad area laser diodes.

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