Self-aggregation of InAs quantum dots on (N11) GaAs substrates

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Abstract

We have fabricated InAs quantum dots on a wide range of substrate orientations with different coverages. We show that the range of GaAs substrate orientations capable of dot self-aggregation is quite wide and that substrate orientation heavily affects ground state electronic properties. We report the low temperature photoluminescence (PL) characterization of quantum dots grown on GaAs with InAs deposition on eight surfaces intermediate between (100) and (111), namely (N11)A/B GaAs substrates, where N ranges from 2 to 5, and on a (100) substrate chosen for comparison purposes. For each substrate orientation, three different amounts of InAs were deposited. At 2 K, all the samples show PL of evident quantum dot origin with an efficiency comparable to that of samples grown on (100) substrates. PL spectra show inhomogeneously broadened, structured peaks in the 1.1–1.4 eV range. The quantum dots grown at low InAs coverages deserve a special interest because of their narrow (25 meV) emission linewidth.

Keywords: Self-aggregation; InAs quantum dots; (N11) GaAs

1. Introduction

Self aggregated (InGa)As/GaAs quantum dot (QD) structures have demonstrated their powerful potential as active layers for a new generation of optical light sources like injection laser devices [1]. The growth of these systems is performed by molecular beam epitaxy in the Stranski–Krasantanov (SK) regime [2], which allows for the nucleation of high quality islands capable of quantum confinement effects in all directions [3]. Both present-day studies and the future device applications of these structures require precise control of properties such as shape, size, density and arrangement of the dots. The parameters generally considered to control these features are the set of conditions (temperature, rates and fluxes) used during the deposition.

Another approach, recently explored by several groups [4,5], makes use of deposition on high Miller index surfaces in order to provide different chemical potentials for the deposited species thus affecting adsorption, migration and desorption processes. Besides, the strain relaxation path is determined by substrate orientation and reconstruction possibly favouring the assembly of dots with preferred spatial orientation.

The range of GaAs substrate orientations capable of dot self-organization is quite wide. We report a low temperature PL characterization of InAs/GaAs heterostructures, grown in the SK regime, by depositing three different amounts of InAs on eight GaAs substrates with orientation intermediate between (100) (also grown as reference samples) and (111), for a total of 27 samples. All the samples show typical QD PL spectra, with an efficiency comparable to the QD systems grown on (100) substrates.

2. Experimental details

The samples under investigation were prepared by molecular beam epitaxy (MBE) on semi-insulating GaAs substrates with the following nine orientations: (100), (211)A/B, (311)A/B, (411)A/B and (511)A/B. The surface orientations are within ±0.5°. Each growth run was carried out simultaneously on four different GaAs substrates. For each orientation, three growths were performed increasing the amount of InAs deposited from $\approx 1.0 \times 10^{15}$ to $\approx 1.2 \times 10^{15}$ and $\approx 1.5 \times 10^{15}$ InAs molecules/cm². These values correspond, respectively, to 1.8, 2.3 and 2.8 monolayers (ML) on the (100) surface. Throughout the rest of this paper, monolayer values will refer to the equivalent thickness on (100) surfaces.

Growth progress was monitored by reflection high energy electron diffraction (RHEED). The change from a streaky to a spotty RHEED pattern has been taken to be a fingerprint of
the onset of a three-dimensional growth mode. More details on the growth procedure may be found in Ref. [6].

PL spectra were measured on samples immersed in superfluid $^4$He ($T = 2$ K) with an exciting power density $I_{exc}$ in the range 1–1100 W/cm$^2$. The excitation source was an Ar$^+$ laser and the spot diameter was 150 μm. Luminescence spectra were measured with a Fourier transform spectrometer operating with an InGaAs photodetector and corrected taking into account the system spectral response.

3. Results and discussion

All the samples show a low temperature PL between 1.1 and 1.4 eV (the spectra of the whole set of samples are reported in Ref. [6], Fig. 1). The emission display the typical QD broad and unresolved bands [7–9] due to unavoidable size fluctuations in the QD ensemble (inhomogeneous broadening [10]). The highest emission energy pertains to the 1.8 ML (311)A sample while the low energy side is occupied by dots grown on (100)-oriented substrates and in particular the lowest emission energy is achieved for an InAs deposition of 2.8 ML on this surface. The low coverage side deserves particular attention, because on this side a PL band as narrow as 25 meV on the A faces (sample (311)A) and 40 meV on the B faces (sample (511)B) have been observed (Fig. 1). This should be of major importance for the fabrication of the active layer of QD based injection laser.

As reported previously [6], the emission centroid follows, on average, a simple trend with increasing the Miller index $N$: it increases for (N11)B-grown samples and decreases for (N11)A samples. Both the (N11)A and (N11)B QD emission energy decreases as the InAs coverage increases thus confirming the expected average increase of dot size with InAs coverage.
The QD, grown by self assembling during epitaxial deposition on (311)A, have been previously observed. The FWHM of such PL components approaches the limit observed at the low coverage side (25 meV). For excitation densities up to about 110 W/cm² the spectra scale with \( I_{\text{exc}} \) in a linear way and can thus be considered as an image of the size distribution of QDs in the sample. Such low fluency PL spectra display a large range of shapes, from almost featureless Gaussian line shapes to structured spectra observed tendentially at high coverage (Fig. 2). Such spectral characteristics are the fingerprints of the distribution of sizes indicating the presence of preferred dot sizes (dot families [11,12]). The multimodal spectra have been therefore decomposed in Gaussian peaks, as shown in Fig. 2 (bottom panel). The parameters of the different Gaussian component (QD families) making up our spectra are reported in Fig. 3, where the energy position (inversely proportional to dot size) and the FWHM (proportional to the size dispersion) of each single component is indicated. At low coverage (1.8 ML) the QD distribution starts on the high energy-low FWHM side of the graph and then develops, at the same coverage, by changing the growth substrate to lower energies and higher dispersions. This behaviour mirrors the observation, made on (100) grown samples [13], that after the 2D/3D transition the islands grow in size and broaden their size distribution with the increasing coverage. In our case, the differences in size between samples grown nominally at the same coverage may be draw back to the effect of a change in the critical coverage for the 2D/3D growth transition, or to changes in the growth rates depending on the substrates orientation and face [14,15]. At higher coverages the two substrate types display different behaviours. While the QD grown on the B faces show families with size dispersions randomly distributed between 50 and 100 meV, the A substrates on the contrary, after a maximum in the size dispersion reached at 1.25 eV, there is clear tendency for a reduction in size dispersion as the average size increases. This suggests that the growth of QD on the A substrates at high coverages favours the assembly of large QD with a narrow size distribution. The FWHM of such PL components approaches the limit observed at the low coverage side (25 meV).

The QD, grown by self assembling during epitaxial deposition on (311)A, have been previously observed to exhibit a non-conventional, faceted, arrowhead-like shape aligned in the [−233] direction. The dot photoluminescence emission was partially (≈13%) polarized along the same [−233] direction. The presence and the sign of the emission polarization can be theoretically associated with the ratio between width and length of the QD along the [−233] direction. In Ref. [15] the evidence of a size dependence of the emission polarization was not conclusive, the range of available sizes were not so large, so giving results compatible with the null hypothesis (no dependence on size of the PL polarization). Working with a wider size range (from 1.8 to 2.8 ML coverage) we performed a more accurate analysis of the tendency with the size of the polarization ratio \( \rho = (I_{[−233]} − I_{[01−]})(I_{[−233]} + I_{[01−]}) \) (where \( I_{[−233]} \) and \( I_{[01−]} \) are the integrated PL intensities along the [−233] and the [01−] directions, respectively), and therefore of the evolution of the width/length ratio of the dots, with increasing coverage. Table 1 reports the measured polarization ratio for the three different coverages. The data confirm the previous observation [16]. Table 1 shows that the polarization ratio is independent on the coverage (and therefore of the QD size). This permits one to infer a uniform growth of the (311)A QDs which retain the same width/length ratio while changing the size.

### 4. Conclusions

We have presented a systematic PL investigation of QD electronic ground state properties for different substrate orientations. All of the eight non-conventional substrate orientations employed allow QD assembly under growth conditions optimized for the (100) surface. Even in non-optimized conditions, the PL efficiency of low coverage samples is equivalent to that of (100) reference samples. A narrow dot distribution was achieved for all the substrates orientations and for both A and B faces with an InAs coverage near the 2D/3D growth transition. Such structures deserve special interest both because of their PL efficiency and because of their narrow (25–40 meV) emission linewidth. On A substrates, low FWHM PL lines may be also achieved at high coverage. Shape anisotropy of (311)A grown QD has been investigated at different coverages by mapping the polarization ratio. No dependence of the polarization ratio on the dot size has been observed.

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### References