Low density InAs quantum dots on GaAs.

E.S. Semenova, A.E. Zhukov, A.Yu. Egorov, A.P. Vasil'ev, N.A. Maleev,
N.V. Kryzhanovskaya, A.G. Gladyshev, Yu.G. Musikhin, M.V. Maximov, V.M. Ustinov

A.F. Ioffe Physico-Technical institute, RAS, 194021, St. Petersburg, Russia
E-mail: esemenova@mail.ioffe.ru

Abstract
*Surface density of self-organized InAs quantum dots in a GaAs matrix was correlated to MBE growth conditions. Surface density as low as 2*10^9 cm^{-2} was achieved.*

A number of devices that exploit quantum dots (QD) is currently growing extremely fast. For certain applications some specific properties of QD array are of most importance. There is therefore a significant interest in forming QDs with predefined properties characteristics (emitting wavelength, surface density, etc.) [1]. In particular, single-photon emitter requires a few, preferably one, active QDs in its active region. As the typical surface density of Stranski-Krastanow QDs is in mid of 10^{10} cm^{-2} an optical microcavity with lateral dimensions of 0.3*0.3 μm^2 accommodates as many as 50 dots. The QD surface density should be reduced down to 1-2*10^9 cm^{-2} or even lower to meet the requirements of single-photon applications.

In the present work we study a tunability of surface density of InAs QDs grown by molecular-beam epitaxy on GaAs substrates. Effect of InAs growth rate, substrate temperature and growth interruption was investigated. The minimum density achieved is about 2*10^9 cm^{-2}.

The structures under investigation were grown on GaAs (100) substrates using a Riber 32P MBE setup. Reflection high-energy electron diffraction (RHEED) pattern was *in situ* monitored to control surface morphology of epilayers and formation of QDs. The substrate temperature was measured using IR pyrometer. QDs density was evaluated by transmission electron microscopy (TEM). Photoluminescence (PL) measurements were conducted in the 77-300K temperature range with an Ar^+ laser (W=200 W/cm^2, λ=514 nm).

The structures comprise the following set of layers: 0.2μm-thick GaAs buffer, 0.1μm-thick $Al_{0.3}Ga_{0.7}As$ barrier, GaAs matrix of 0.1μm, array of InAs QDs capped with 5nm-thick low temperature (LT) GaAs followed by 20nm-thick GaAs layer. Deposition temperature of QDs and LT GaAs was varied in the 485-530^{0}C range. All the rest was grown at 600^{0}C. In some structures QD array was immediately protected by LT GaAs while in some others growth interruption was applied just after QD deposition.

In sample #0 (see Table 1) 1.7ML of InAs was deposited with growth rate of 0.25 A/s at 485^{0}C. This set of parameters can be treated as conventional conditions for MBE-grown QDs providing the surface density ~5-6*10^{10} cm^{-2} with PL peak around 1.18 μm at room temperature.

First we studied the effect of growth interruption, see sample #1 in Table 1. As RHEED pattern came to spotty, In effusion cell was closed and the growth surface was then kept under As_4 pressure during 100 sec. Growth interruption results in certain increase of QDs size. PL peak position reaches the wavelength of 1.22 μm which is a sign of In atoms migration during growth

interruption. However decrement of surface density of QDs is only 30% ($4.2*10^{10}$ cm^{-2}) as compared to the conventional growth conditions.

Next the effect of higher growth temperature was studied, see sample #2. QDs with effective thickness of 2.3ML were deposited at 530^0C with 85sec-long growth interruption. InAs re-evaporation rate at this substrate temperature was previously estimated as 0.06 A/s. It means that during 85 sec interruption approximately 1.7ML of InAs is off. The residual thickness of InAs is about 0.9ML that is less than the onset of QD formation (1.7ML). Thus one can expect complete QD disappearance or, at least, significant reduction of the QD density. The estimated QD density in the sample is $7*10^9$ cm^{-2} which is 8 times as low as the conventional that. We believe further increase of growth interruption time and/or substrate temperature would decrease QD density more. This study is in progress.

Finally, influence of lowered growth rate was studied. In sample #3 InAs with effective thickness of 2.3 ML was deposited at 485^0C. InAs growth rate was reduced down to 0.057 A/s resulting in QD surface density of $1.6*10^{10}$ cm^{-2}. Further decrease of growth rate (0.021 A/s) in the combination with slightly higher substrate temperature (505^0C) and growth interruption of about 20 sec. provides the surface density as low as $2*10^9$ cm^{-2} (sample #4).

In summary TEM study of QD samples grown under different MBE conditions revealed that a combination of lowered growth rate of InAs, elevated substrate temperature and growth interruption after QD formation can provide the QD surface density as low as $2*10^9$ cm^{-2}. This figure is well suitable for purpose of single-photon devices.

Acknowledgement
This study was partly supported by the Russian Foundation for Basic Research, the Joint Scientific Program of the Ioffe Physicotechnical Institute and Nanosemiconductors Gmbh, Germany and Ioffe-ITRI Joint Scientific Program.

Table 1.

Growth conditions and characteristics of QD samples.

#	V_{InAs}, A/sec	Q_{InAs}, ML	Tsub, C	Growth interruption, sec	QD density, cm^{-2}	Wavelength (RT), nm
0	0.25	1.7	485	No	6E10	1180
1	0.25	1.7	485	100	4.2E10	1228
2	0.26	2.3	530	85	7E9	1042
3	0.057	2.3	485	No	1.6E10	1202
4	0.021	2.3	505	20	2E9	1087

References

[1] V.M. Ustinov, A.E. Zhukov, A.Yu.Egorov, N.A.Maleev, “Quantum Dot Lasers”, Oxford University press, 2003.