KINETIC MECHANISMS OF QUANTUM DOT FORMATION IN HETEROEPITAXIAL SYSTEMS

G.E.Cirlin[a-c], *V.G.Dubrovskii*[a], *Yu.G.Musikhin*[a], *Yu.B.Samsonenko*[b], *A.A.Tonkikh*[a-c], *N.A.Krizhanovskaya*[a], *N.K.Polyakov*[a,b], *N.V.Sibirev*[b], *V.M.Ustinov*[a] *and P. Werner*[c]

[a]Ioffe Physical Technical Institute of the Russian Academy of Sciences
Politekhnicheskaya 26, 194021, St.-Petersburg, Russia
[b]Institute for Analytical Instrumentation of the Russian Academy of Sciences, Rizhsky 26
190103, St.-Petersburg, Russia
[c]Max-Planck Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

cirlin@beam.ioffe.ru

In recent years, quantum dot (QD) heterostructures have attracted a continuously increasing interest from the viewpoints of fundamental physics and promising device applications, in particular in quantum dot lasers and other advanced optoelectronic devices [1]. The main method to fabricate dense ensembles of QDs is their self-organized growth in highly mismatched heteroepitaxial systems such as InAs/GaAs, Ge/Si and many others. One of the critical issues in physics and technology of QDs is the development of reliable growth techniques with the controllably structured QDs. In this work we present an overview of our recent results on the kinetically controlled engineering of QD ensembles with the desired structural properties.

First of all, we present a kinetic theory of stress-driven formation of coherent islands in the Stranski-Krastanow growth mode [2]. This theory describes process of coherent island formation as the first order phase transition under strongly non-equilibrium conditions. The superstressed wetting layer plays the role of a metastable condensing phase, the coherent strained islands are the nuclei of a new phase, while the metastability is ensured by the material flux onto the surface. The thermodynamic driving force for QD formation is the stress relaxation in 3D islands. The kinetic mechanism of island growth is the stress-driven diffusion of material from wetting layer to islands. The end result of numeric simulations is the detailed dynamic description of island size distribution and wetting layer thickness. At given material constants of particular heteroepitaxial system, we present the kinetic structural diagrams that provide the characterization of QD ensembles in terms of their size and density as functions of technologically controlled growth conditions. The kinetic nature of critical thickness of 2D-3D transition, the possibility to observe subcritical QDs, the transition from thermodynamically to kinetically controlled regimes of QD formation and several other effects are discussed.

In the experimental part of the work we demonstrate the results of growth experiments in the IaAs/GaAs(100) and the Ge/Si(100) systems obtained by different diagnostics techniques [3]. The structural and optical properties of QD ensembles grown by molecular beam epitaxy (MBE) at different conditions (surface temperature T, deposition rate V, total amount of deposited material, exposition time) are studied by reflection high energy electron diffraction (RHEED), atomic force microscopy (AFM), transmission electron microscopy (TEM) and photoluminescence (PL) methods. The obtained experimental data are compared to the results of simulations and a quantitative correlation between them is analyzed. Some of the graphs obtained for the InAs/GaAs system are shown in Fig.1. These results, in particular, demonstrate that the deposition rate has an important impact on the structure of QD ensembles and may be used as a control parameter to tune the surface morphology. Similar structural diagrams for the Ge/Si system are presented. The recent results on the formation of subcritical InAs/GaAs QDs (1.5-1.6 monolayer thickness range) are discussed. The influence of Sb flux on the structure of Ge/Si QDs is studied and analyzed within the frame of developed theory. In conclusion, the opportunities for the kinetically controlled engineering of QD ensembles in different heteroepitaxial systems are discussed. Numerous examples of the application of developed kinetic approach to the QD formation are given.

The authors are grateful to the financial support received from different scientific programs of the Russian Academy of Sciences, SANDiE and RFBR grant № 05-02-16568.

References:

[1] V.M.Ustinov, A.E.Zhukov, A.Yu.Egorov, N.A.Maleev "Quantum dot lasers" Oxford university press 2003.
[2] V.G.Dubrovskii, G.E.Cirlin, V.M.Ustinov, Phys.Rev.B 68, (2003) 075409.
[3] V.G.Dubrovskii, G.E.Cirlin, Yu.G.Musikhin, Yu.B.Samsonenko, A.A.Tonkikh, N.K.Polyakov, V.A.Egorov, A.F.Tsatsul'nikov, N.A.Krizhanovskaya, V.M.Ustinov and P.Werner, J.Cryst.Growth 267(1-2) (2004) 47.

Figures:

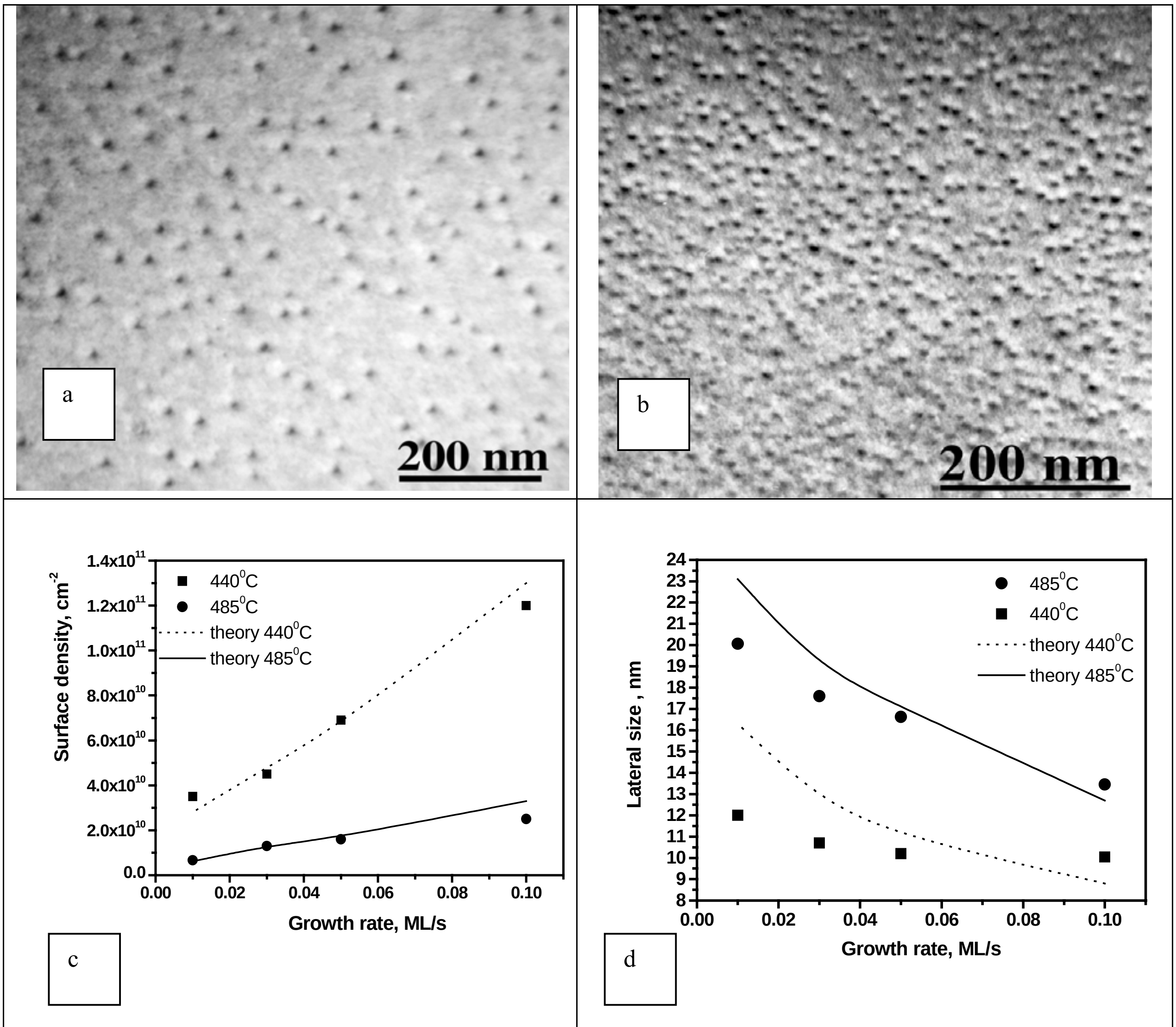

Fig.1. a – TEM image of 2 monolayer ensemble of InAs/GaAs QDs grown at T=485^{0}C, V=0.03 ML/s, b – same at T=440^{0}C and V=0.05 ML/s, c – density of InAs/GaAs QDs versus growth rate at two different T, d – QD lateral size versus growth rate at two different T.