EFFECT OF GROWTH CONDITIONS ON InAs NANOISLANDS FORMATION ON Si(100) SURFACE*)

G.E. CIRLIN**), N.K. POLYAKOV, V.N. PETROV, V.A. EGOROV, YU.B.SAMSONENKO**)

Institute for Analytical Instrumentation, Russian Acad. Sci., Rizhsky 26, 198103 St. Petersburg, Russia.

D.V. DENISOV, V.M. BUSOV, B.V. VOLOVIK, V.M. USTINOV, ZH.I. ALFEROV, N.N. LEDENTSOV†)

A.F. Ioffe Physico-Technical Institute, Russian Acad. Sci., Politechnicheskaya 26, 194021 St. Petersburg, Russia

D. BIMBERG

Institut für Festkörperphysik, Technishe Universität, Hardenbergstrasse 36, D–10623 Berlin, Germany

N.D. ZAKHAROV, P. WERNER

Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D–06120 Halle (Saale), Germany

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In this paper we have studied the island formation during InAs/Si(100) three dimensional (3D) heteroepitaxial growth using RHEED, SEM and TEM methods. We have found the strong influence of the growth conditions on the surface morphology. Both kinetic and energetic parameters play an important role during the growth in InAs/Si system. Dislocation–free InAs islands are formed at the Si(100) when lateral size is less then 5 nm.

1 Introduction

Self-organisation effects at the semiconductor surfaces during molecular beam epitaxy (MBE) and related techniques have attracted strong interest during last decade. This is due to both fundamental aspects and possible applications in modern opto and microelectronics. For example, lasers in which carriers are confined in quantum dots (QDs) active region should increase the characteristic temperature and decrease threshold current density. A realisation of QDs lasers in the

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**) Also at *A.F.Ioffe Physico-Technical Institute RAS, Politechnicheskaya 26, 194021 St.Petersburg, Russia*

†) Also at *Institut für Festkörperphysik, Technishe Universität, Hardenbergstrasse 36, D–10623 Berlin, Germany.*

(In,Ga,Al)As/GaAs heteroepitaxial system showing a practical advantages of the nanostructured materials has been demonstrated recently [1–3].

However, silicon is a key material in modern semiconductor industry. Most of the electron devices are fabricated on a Si substrate. Silicon is less suitable for optoelectronic applications because of its indirect band gap nature. For the integrated circuits with "on-the-same-wafer" coexistence of opto- and microelectronic elements it is desirable to increase the luminescence efficiency of silicon. Different approaches were used in order to solve the problem of improving the silicon optical properites, including Er-doped silicon [4], porous [5] or nanostructured strained layers in Ge/Si system [6].

An alternative way has been proposed recently in [7], namely a formation of narrow gap direct-band material QDs in a Si matrix. Recently we demonstrated a possibility to create nanoscale InAs islands on Si(100) surface directly during MBE growth [8]. It was shown that under certain growth conditions InAs/Si heteroepitaxial growth proceeds via 3D growth mode depending on the substrate temperature and the As/In flux ratio [9,10]. Such QDs capped with a Si layer shows a luminescence band in the 1.3 μm spectral region [11] which is important for, *e.g.*, fiber optics applications. In this paper we will concentrate on the structural properties of InAs/Si(100) quantum dots fabricated during MBE growth regimes providing growth mechanism when islanding initiates before the first monolayer of InAs is completed. We studied these properties using methods of Reflection High Energy Electron Diffraction (RHEED), Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM).

2 Experimental

The samples were grown on exactly oriented Si(100) p–type substrates using a Riber Supra MBE setup. The silicon substrates were chemically prepared using a standard procedure described in [12]. The native oxide layer was removed in a growth chamber at a substrate temperature $T_s = 850$°C. After 15 min annealing well resolved mixed (2×1) and (1×2) surface reconstruction appeared. Then a Si buffer layer nominally 500 Å thick was grown at a Si growth rate of 1 Å/sec and $T_s = 600$°C. Examination of the surface after this stage with scanning tunneling microscopy reveals atomically smooth surface with no appearance of 3D features. The next step was InAs deposition in the conventional MBE growth mode at gradually decreased substrate temperature down to 350°C. During the experiments, the following conditions were used: InAs growth rate of 0.1 monolayers (ML) per second, As/In flux ratio of 3 or 10. At these growth regimes, the formation of 3-dimensional (3D) InAs islands occurs via 3D growth when islanding starts before formation of first monolayer of InAs [10]. After the deposition of the desired amount of InAs was completed samples were quenched to room temperature and removed from the growth chamber.

During the growth, the surface morphology was monitored by RHEED technique using a specially designed system for registration and analysis of the RHEED patterns [13] composed of a high sensitivity video camera, video tape recorder and a computer, all interconnected via digital interface. SEM measurements were performed using CamScan setup. High resolution TEM images were taken with JEOL 4000EX microscope.

3 Results and discussion

Analysis of the RHEED pattern evolution shows that under the explored growth conditions the 2D–3D surface transformation was observed at (0.7 ± 0.02) ML or (0.8 ± 0.02) ML at As/In fluxes ratio 3 and 10, respectively (within accuracy of the determination of the moment when 3D features appeared [14]). Hence we observed a formation of 3D islands on the bare substrate. In Fig. 1a,b RHEED patterns before the deposition of InAs (a) and after the growth of 0.9 ML of InAs (b) are presented. In addition to the streaks responsible for the flat Si(100) surface in Fig. 1a, spotty-like features appeared on RHEED pattern (Fig. 1b) with a distance (in reciprocal space) approximately 10 % less then that between Si streaks. (Note that the lattice mismatch between InAs and Si is approximately 11 %).

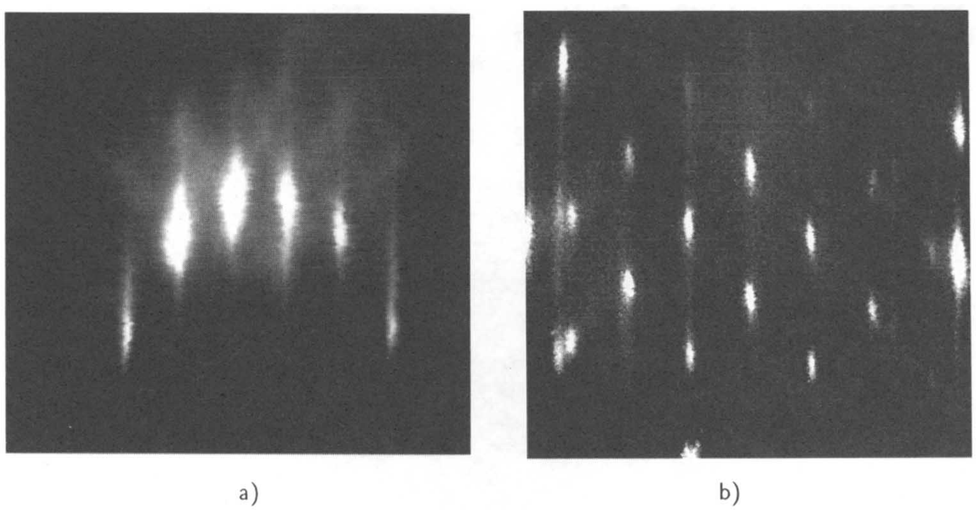


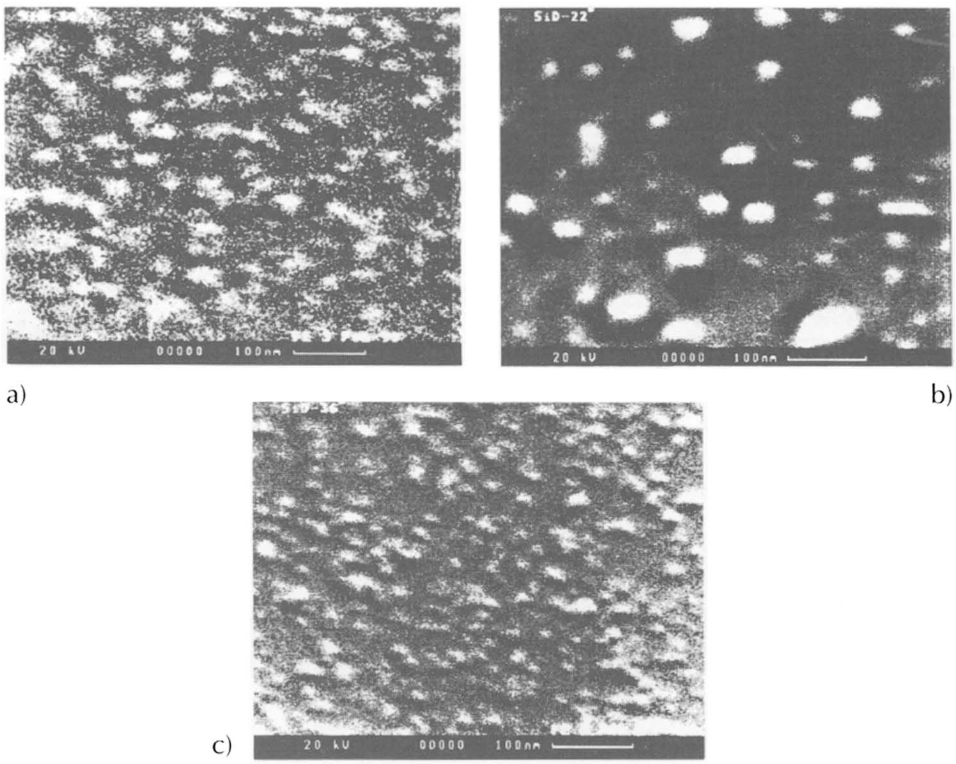
Fig. 1. *RHEED pattern before (a) and after (b) deposition of 1 ML InAs on Si(100) surfrace via 3D growth mode taken along [011] direction.*

In order to clarify how growth parameters influence the surface morphology we grew three samples, labelled 1–3. Their MBE technological conditions and geometrical characteristics are presented in the Table 1. Figure 2a–c shows typical SEM images for the samples 1–3, respectively.

The main trends for the InAs/Si island growth are the following. For higher As pressure and the same InAs mean thickness the island size becomes smaller as compared to the case of decreased As/In fluxes ratio (samples 1 and 3). We

Table 1. Growth conditions and geometrical characteristics of the InAs/Si(100) quantum dot samples.

Sample No.	InAs thickness, ML	As/In fluxes ratio	Island lateral size (nm)	Surface density of islands ($10^{10}cm^{-2}$)
1	1.2	3	15–50	4
2	2.5	3	20–80	1.6
3	1.2	10	3–15	16



a) b) c)

Fig. 2. SEM images (a–c) of the samples labelled 1–3 in Table 1, respectively. Sides of the images are parallel to [011] and [01$\bar{1}$] directions.

believe that this is due to the suppression of the surface migration length. The density of the islands for sample 3 was four times higher than that of sample 1. The islands size distribution becomes narrower, too. With increasing the average InAs thickness (sample 2) the islands start to form large conglomerates. These clusters are elongated and exhibit crystallographic shape with the base oriented along [011] and [0$\bar{1}$1] directions. Similar situation was observed in [15] where such clusters formed during InAs growth on Si(100) passivated (hydrogen-terminated) surfaces with approximately same size and surface density. We note that for the sample 2 the critical thickness is exceeded by the value of 1.8 ML, *i.e.* 2.5 times higher. In InAs/GaAs heteroepitaxial system such excess thickness and large sizes should lead to the formation of dislocations. In order to check crystalline quality we examine the same samples with cross-sectional TEM.

Most of the islands exhibit considerably good crystalline quality although misfit dislocations appeared at the InAs/Si interface. In Fig. 3 cross-section TEM image for single InAs nanoisland is presented. From TEM data we have found that a critical lateral size of the coherent dislocation-free islanding is equal to (2–5) nm depending on the island height. Islands having larger size are defected due to misfit dislocations.

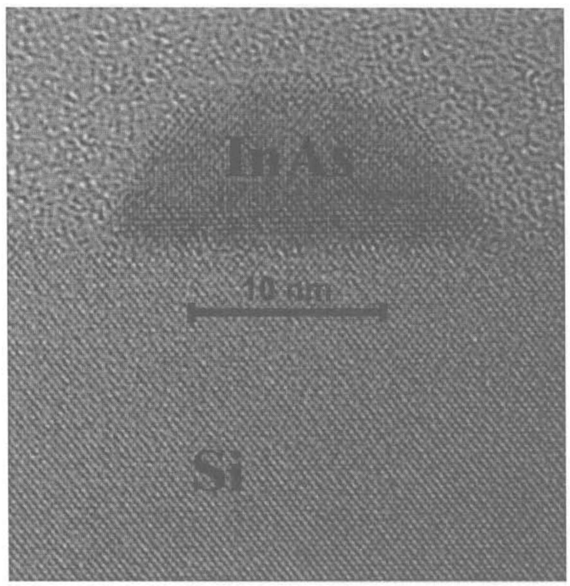


Fig. 3. Typical high resolution cross-section TEM image of single InAs nanoscalė island at Si(100) surface.

In conclusion, we have examined an islanding appearance during InAs/Si(100) 3D growth with different electron diffraction and microscopy methods. We have found the influence of the growth parameters on the surface morphology, showing that both kinetics and energetics play an important role in InAs/Si system. Dislocation-free InAs islands are formed at the silicon surface when their lateral size is less then 5 nm.

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