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Experiment Report Form

The double page inside this form is to be filled in by all users or groups of users who have had access to beam time for measurements at the ESRF.

Once completed, the report should be submitted electronically to the User Office using the **Electronic Report Submission Application:**

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The Review Committees reserve the right to reject new proposals from groups who have not reported on the use of beam time allocated previously.

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Deadlines for submission of Experimental Reports

- 1st March for experiments carried out up until June of the previous year;
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Instructions for preparing your Report

- fill in a separate form for each project or series of measurements.
- type your report, in English.
- include the reference number of the proposal to which the report refers.
- make sure that the text, tables and figures fit into the space available.
- if your work is published or is in press, you may prefer to paste in the abstract, and add full reference details. If the abstract is in a language other than English, please include an English translation.

ESRF	**Experiment title:** Electronically coupled 3D periodic arrangement of SiGe quantum dots	**Experiment number:** SI-1693
Beamline: ID10B	**Date of experiment:** from: 2.7.2008 to: 8.7.2008	**Date of report:** 18.8.2008
Shifts: 18	**Local contact(s):** Jiri Novak	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

Prof. Dr. Vaclav HOLY
Prof Dr. Guenther BAUER
Dr. Detlev GRUETZMACHER
Dr. Julian STANGL
*Dr. Ondrej Caha
*Nina Hrauda
*Tomas Cechal

Report:

One of the main aims of research on semiconductor quantum dots is to create electronically coupled systems with tunable electron wave function overlap. Such systems with artificially created electronic band structures will be useful for nanophotonic devices (solid state sources and detectors for specific wavelengths). Using prepatterned Si substrates the growth of two-dimensional periodic arrangements of SiGe islands is by now a technique, which is mastered by several laboratories. So far patterns with periodicities in the range between 200 nm and 1 μm were achieved by optical or e-beam lithography and subsequent reactive etching ion techniques [1]. The distribution of elastic strains in such three-dimensional arrays of SiGe quantum dots has been investigated in detail by high-resolution synchrotron x-ray diffraction and strain simulation [2]. These systems, however, do not exhibit the wave-function overlap, so that their electronic and optical properties are of less importance.

For periodicities below 100 nm another technique was employed, namely extreme ultra-violet interference lithography (EUV-IL) at a wavelength of λ= 13.5 nm using diffractive optics for fast exposure. Using this approach, Si (001) templates with perfect periodicity down to less than 30 nm have been realized at a dedicated beamline of the Swiss Light Source in Villigen [3]. On these substrates, two- and three- dimensionally ordered SiGe quantum dot crystals with the so far smallest quantum dot sizes and periods both in lateral and vertical directions have been grown by molecular beam epitaxy [4]. On the prepatterned Si substrates Ge is deposited which forms {105} facetted islands in the 2D pit arrangement. These islands are capped with a Si layer, on top of which few monolayers of Ge are deposited and coalesce into islands. Typically 10 periods of SiGe islands separated by Si spacer layers are grown. Whereas the ordering of the SiGe quantum dots in the first layer is imposed by the periodically patterned Si substrate, after capping with Si, in the subsequent layers the strain fields of the buried quantum dots are used to order the islands three-dimensionally.

The strain and morphology analysis of short-periodic three-dimensional quantum dot arrays with wave-function overlap has been performed during the reported experiment for the first time. We have investigated two SiGe quantum dot samples: sample U047 consisted in a single layer of nominally pure Ge quantum dots fabricated onto a lithographically patterned Si(001) buffer layer, the dots created a periodic square array with the lateral period of 70 nm; sample U048 was a Ge/Si dot multilayer with 10 Ge/Si bilayers, thickness of the Si spacer layers was 6 nm and the lateral period of the square patterning of the Si buffer was 70 nm. The size of the patterned area of the buffer surface was 100x100 μm^2. Figure 1 shows AFM pictures of the surface of both samples, above the patterned area; the perfect periodicity of the dot arrays is obvious. From the figure it also follows that the size homogeneity of the dots improves with the number of multilayer periods; the dots in sample U048 are much more uniform than in sample U047.

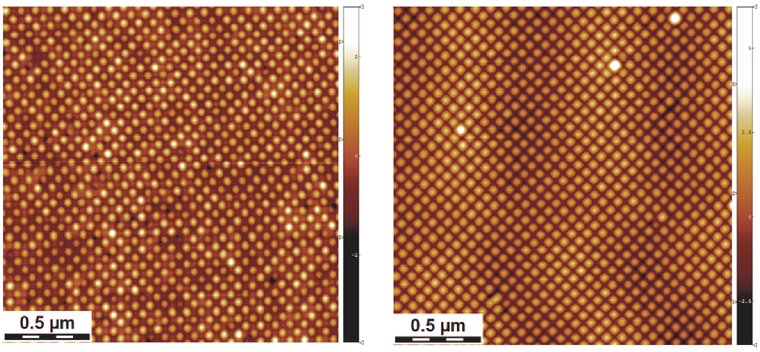

Fig. 1 AFM pictures of the patterned areas of samples U047 (left) and U048 (right)

We have carried out a series of diffraction measurements using the photon energy of 8 keV. The primary beam was vertically focused by a bent multilayer mirror, the final size of the primary beam of 40x80 μm^2 was achieved by a cross-slit close to the sample. The diffracted intensity has been detected by a two-dimensional CCD detector placed in the distance of about 70 cm from the sample. The optimum sample position was found by a scan of the sample across the primary beam. For each sample we have measured two three-dimensional (3D) reciprocal-space distributions of diffracted intensity around the reciprocal latttice points 004 (symmetric diffraction) and 224 (asymmetric diffraction, grazing exit). The 3D intensity maps have been collected in the omega/2theta scanning mode, i.e., by a simultaneous rotation of the sample and the detector arm, the latter with the double angular velocity.

Each 3D map contains approx. 1000x1000x1000 pixels, we have transformed the measured intensity to reciprocal space, where q_x and q_y axes are parallel to the sample surface, the diffraction vector $\boldsymbol{h}$ (004 or 224) lies in the vertical q_xq_z plane.

As a representative example, we present in Fig. 2 the reciprocal-space distributions of the intensity diffracted from samples U047 and U048 in diffraction $\boldsymbol{h}$ = 004.

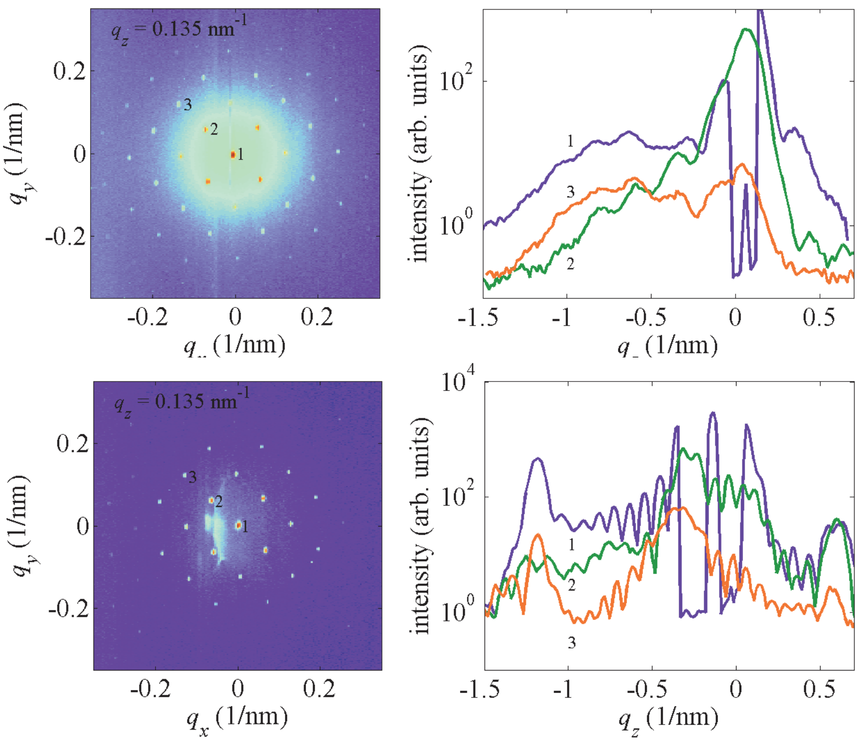

Fig. 2 Intensity distributions in the q_xq_y plane parallel to the sample surface (left) and the linear scans along q_z through the satellites denoted 1, 2 and 3 (right panels) of samples U047 (upper row) and U048 (lower row). The intensity drops on the q_z scans across the 0-th satellite (denoted 1) are caused by the beam stop inserted during the acqusition of several CCD frames.

The horizontal intensity maps (the left column) exhibit lateral satellites; due to the ideal lateral periodicity of the dots the widths of the satellites are determined only by the resolution function of the experimental set-up. The panels in nthe right column of Fig. 2 depict the vertical q_z-scans extracted from the 3D intensity map, crossing the lateral satellites denoted 1, 2 and 3. In the case of the multilayer sample U048, the vertical satellites are visible, stemming from the vertical periodicity of the 3D dot array.

Recently, we are dealing with the simulation of the 3D intensity map based on kinematical approximation and finite-element simulation of the strain field. We expect to obtain a detailed information on the shape and local chemical composition in the quantum dots; these data will enable us to calculate theoretically the wave functions of electrons and holes confined in the strained Si (surrounding the dots) and in the dots and their overlap.

[1] Z. Zhong et al., Appl.Phys.Lett. **82**, 4779 (2003), Z.Zhong et al., Phys.Rev.Lett. **95**, 176102 (2007).

[2] J. Novak et al., J. Appl. Phys. **98**, 073517 (2005).

[3] H.H. Solak, Microelectronic Engineering **78-79,** 410 (2005)

[4] C. Dais et al. Surface Science **601**, 2787 (2007).