L-05

INVESTIGATION OF SELF-ORGANIZED SEMICONDUCTOR QUANTUM DOTS BY SYNCHROTRON RADIATION SCATTERING

V. Holý[1]*, O. Caha[2], J. Novák[2], J. Stangl[3], and G. Bauer[3]

[1]*Dept. of Physics of Electronic Structures, Charles University Prague, Czech Republic (* holy@karlov.mff.cuni.cz)*
[2]*Institute of Condensed Matter Physics, Masaryk University Brno, Czech Republic*
[3]*Institute of Semiconductor Physics, Kepler University Linz, Austria*

Processes of self-organization during the growth of semiconductor heterostructures are extensively studied, due to their prospective application for fabrication of semiconductor nanostructures (quantum wires and dots). Since the self-organizing growth of these structures is of a probabilistic nature, resulting ensembles of nanostructures suffer from statistical variations of positions, shapes, sizes, and chemical composition. A reliable non-destructive method for the determination of these parameters is therefore necessary for the study of self-assembling mechanisms and for an optimization of the growth process.

The application of x-ray scattering for this purpose is complicated by extremely small volumes of quantum dots and wires, so that the application of an intense synchrotron source is inevitable. Moreover, in order to enhance the useful signal from the nanostructures and to suppress the contribution of the substrate, a surface-sensitive scattering geometry must be used, namely grazing-incidence small-angle x-ray scattering (GISAXS) and grazing-incidence diffraction (GID) [1].

The GISAXS method is not sensitive to the elastic strains in and around the nanostructures and the distribution of its signal in reciprocal space is, roughly speaking, proportional to the square of the Fourier transformation of the positions and shapes of the nanostructures in the scattering sample. The method has been used for the determination of the shapes of quantum wires [2] and dots (see, among others, [3-6]). If the nanostructures are arranged periodically on the surface or on the interfaces in a multilayer, the intensity distribution in reciprocal space exhibits periodically arranged satellite maxima, the widths of which depend on the degree of periodicity of the arrangement [5,7].

Grazing-incidence diffraction is sensitive both to the shapes and to the elastic strains in the nanostructures, the latter depends on the local chemical composition in the dots [1]. In order to distinguish both effects, two methods have been developed, namely iso-strain scattering [8] and anomalous-scattering [9,10]. The former approach is based on the eikonal approximation that assumes that the intensity scattered into a certain point in reciprocal space stems from an iso-strain volume in the quantum dot having a given strain status; this approximation is valid for larger objects. Using this approach, both the shape and local chemical composition of free-standing quantum dots can be determined from a measured three-dimensional reciprocal-space distribution of diffracted intensity. The latter method utilizes a steep energy dependence of the scattering factor close to an absorption edge; comparing the intensity distribution measured at the energies close to and far away from an edge, the size and local chemical composition of free-standing dots can be determined as well. Recently, from an energy-dependent anomalous scattering in GID, the local neighborhood of atoms in chosen iso-strain volume was determined, by combination of GID and EXAFS methods (extended diffraction anomalous fine structure spectroscopy – EDAFS [11]).

In this talk, we do not discuss all aspects of synchrotron radiation scattering from self-organized nanostructures, this is the subject of the talk by T.H. Metzger at this conference. Instead, we focus to a particular problem of the application of iso-strain and anomalous scattering methods for quantum dots in a multilayer buried below the sample surface.

The primary x-ray beam irradiating an array of quantum dots distributed on a free surface is reflected from a surface and it creates a standing wave with nodal planes parallel to it. Similarly, the x-rays scattered from the dots create a standing wave pattern as well. Using the iso-strain method, these patterns make it possible to determine the vertical position of a chosen iso-strain volume in a quantum dot above its basal plane. However, such a standing wave pattern does not exist below the sample surface and therefore, this method cannot be used for buried quantum dots. In order to create an analogous standing wave pattern, a two-dimensional array of self-organized InGaAs quantum dots has been grown on the top of a GaAs/AlGaAs periodic superlattice; this superlattice served as a Bragg reflector for primary and scattered x-rays. The quantum dots were overgrown by a GaAs capping layer. Using the GID geometry, we have measured a three-dimensional distribution of the diffracted intensity in reciprocal space. The intensity scattered from the dots creates a broad maximum in reciprocal space, its radial position (parallel to the diffraction vector ***h***) reflects the mean strain in the dot lattice, while the angular width (perpendicular to ***h***) is determined by the dot shape.

Due to the standing wave formed by the GaAs/AlAs reflector underneath, this intensity maximum is modulated by narrow peaks and/or cusps along the direction q_z perpendicular to the sample surface. For a given radial coordinate $q_r \parallel \boldsymbol{h}$, the shapes of these features depend on the vertical position of the iso-strain volume, having the lateral strain $\varepsilon_{\parallel} = -q_r / |\boldsymbol{h}|$. This position can be obtained by comparing the measured intensity distribution along q_z with standing-wave patterns simulated for various vertical coordinates z. Figure 1 shows an example of q_z intensity distributions measured for various q_r's, *i.e.*, for various $\varepsilon_{\parallel}$. The standing-wave maxima make it possible to reconstruct the profile of the lateral strain in the dots; the results of these studies will be published elsewhere.

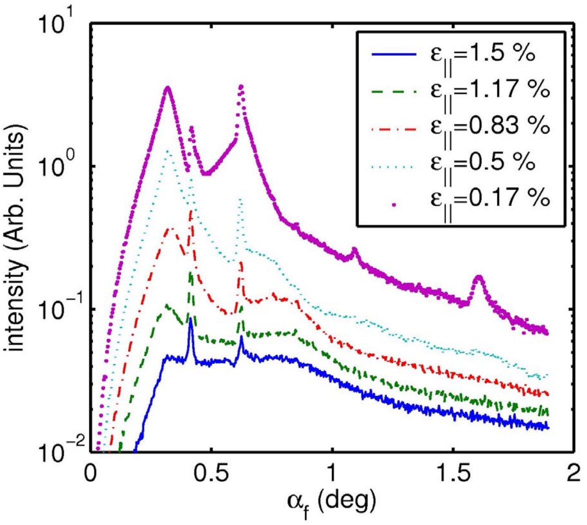

Figure 1. α_f-scans (proportional to q_z) measured on an array of InGaAs quantum dots deposited on an AlGaAs/GaAs Bragg reflector. The measurements have been carried out for various q_r's, corresponding to the given values of $\varepsilon_{||}$.

In the talk, we present several examples of our results on anomalous scattering from superlattices with self-organized nanostructures; only one example is shown in this abstract. During the growth of short-period III-V superlattices (InAs/AlAs, for instance) on a nearly strain-matched (001) substrate, spontaneous lateral modulation of the thicknesses of individual layers is observed along $\langle 100 \rangle$. We have investigated the resulting modulated structures by GID using two wavelengths – a "normal" wavelength of 1.5 Å, and an anomalous one (3.366 Å), for which the chemical contrast between InAs and AlAs disappears in diffraction 200. Therefore, this arrangement is sensitive only to the local strain distribution caused by the lateral modulation and not to the local shape of the interfaces. Figure 2 shows the $q_r q_z$-map of the intensity diffracted in 200 using the anomalous wavelength; the lateral satellites caused by the strain modulation are clearly visible. We have compared this intensity map and an analogous map obtained at 1.5 Å with numerical simulations; from this comparison we were able to determine the shape of the interfaces and the amplitude of the thickness modulation [12,13].

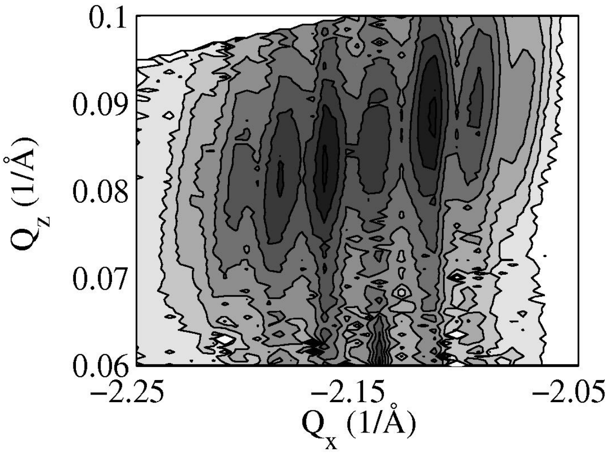

Figure 2. $q_r q_z$ map (denoted as $Q_x Q_z$) taken in the GID geometry, anomalous diffraction 200, InAs/AlAs superlattice with spontaneous lateral modulation.

Acknowledgements: The work has been supported by the Grant agency of Czech Republic (project 202/03/0148). We acknowledge the assistance of the crew of the beamline ID01 at ESRF (T.H. Metzger, B. Krause). The InAs/AlAs superlattices were obtained from Physical and Chemical Science Center, Sandia National Laboratories, Albuquerque, USA (J.L. Reno), the GaInAs quantum dots were grown at MPI Stuttgart (O.G. Schmidt).

References:

[1] J. Stangl, V. Holý, G. Bauer, *Rev. Mod. Phys.* (2004) in print

[2] V. Holý, T. Roch, J. Stangl, A. Daniel, G. Bauer, T.H. Metzger, Y.H. Zhu, K. Brunner, G. Abstreiter, *Phys. Rev. B* **63** (2001) 205318

[3] M. Schmidbauer, Th. Wiebach, H. Raidt, M. Hanke, R. Köhler, H. Wawra, *Phys. Rev. B* **58** (1998) 10523

[4] M. Rauscher, R. Paniago, T.H. Metzger, Z. Kovats, J. Domke, J. Peisl, H.-D. Pfannes, J. Schulze, I. Eisele, *J. Appl. Phys*. **86** (1999) 6763

[5] V. Holý, J. Stangl, G. Springholz, M. Pinczolits, G. Bauer, I. Kegel, T.H. Metzger, *Physica B* **283** (2000) 65

[6] I. Kegel, T.H. Metzger, J. Peisl, P. Schittenhelm, G. Abstreiter, *Appl. Phys. Lett.* **74** (1999) 2978

[7] I. Kegel, T.H. Metzger, J. Peisl, J. Stangl, G. Bauer, D. Smilgies, *Phys. Rev. B* **60** (1999) 2516

[8] I. Kegel, T.H. Metzger, A. Lorke, J. Peisl, J. Stangl, G. Bauer, J.M. Garcia, P.M. Petroff, *Phys. Rev. Lett.* **85** (2000) 1694

[9] R. Magalhaes-Paniago, G. Medeiros-Ribeiro, A. Malachias, S. Kycia, T.I. Kamins, R. Stan Williams, *Phys. Rev. B* **66** (2002) 245312

[10] T.U. Schuelli, M. Sztucki, V. Chamard, T.H. Metzger, D. Schuh, *Appl. Phys. Lett.* **81** (2002) 448

[11] S. Grenier, M.G. Proietti, H. Renevier, L. Gonzalez, J.M. Garcia, J. Garcia, *Europhys. Lett.* **57** (2002) 499

[12] J.H. Li, V. Holý, M Meduňa, S.C. Moss, A.G. Norman, A. Mascarenhas, J.L. Reno, *Phys. Rev. B* **66** (2002) 115312

[13] O. Caha, to be published