ISSN 1063-7842, Technical Physics, 2009, Vol. 54, No. 4, pp. 561–568. © Pleiades Publishing, Ltd., 2009.
Original Russian Text © L.I. Goray, N.I. Chkhalo, G.E. Tsyrlin, 2009, published in Zhurnal Tekhnicheskoĭ Fiziki, 2009, Vol. 79, No. 4, pp. 117–124.

OPTICS, QUANTUM ELECTRONICS

Determining Angles of Incidence and Heights of Quantum Dot Faces by Analyzing X-ray Diffuse and Specular Scattering

L. I. Goray[a, b], N. I. Chkhalo[c], and G. E. Tsyrlin[a, d]

[a] Institute of Analytical Instrument Making, Russian Academy of Sciences, Rizhskii pr. 26, St. Petersburg, 190103 Russia
[b] International Intellectual Group, Inc., 10313 Slated Island, New York, USA
[c] Institute for Physics of Microstructures, Russian Academy of Sciences, ul. Ul'yanova 46, Nizhni Novgorod, 603950 Russia
[d] St. Petersburg Physics and Technology Center for Research and Education, Russian Academy of Sciences, ul. Khlopina 8, St. Petersburg, 195220 Russia
e-mail: lig@skylink.spb.ru

Received February 5, 2008

Abstract—Scattering of X rays by structures with multilayer ensembles of quantum dots MBE-grown in the In(Ga)As–GaAs system is studied by high-resolution grazing X-ray reflectometry. The peaks of the diffuse scattering intensity are discovered for the first time in structures with both vertically uncorrelated and vertically correlated quantum dots. It is shown that the position of the peak is totally determined by angle of inclination α of the quantum dot pyramidal faces (the so-called blaze condition for diffraction gratings), which was theoretically predicted earlier. Comparison with the results of scattering simulation carried out by the technique of boundary integral equations indicates that a simple geometrical condition allows one to exactly determine the value of α from the position of the intensity peak, the shape of which depends on many parameters. As follows from the theory and experiment, the width and height of the peaks for samples with vertically correlated quantum dots are larger than for those with uncorrelated dots. The roughness and interdiffusion of interfaces and the height of quantum dots are found from the position and amplitude of Bragg peaks. Thus, the conventional application of high-resolution grazing X-ray reflectometry is extended in this work to determination of the quantum dot geometry.

PACS numbers: 42.25.Dd, 42.25.Fx, 61.05.C-, 68.65.-k

DOI: 10.1134/S1063784209040185

INTRODUCTION

Low-temperature structures, such as quantum dots (QDs), quantum molecules, and quantum dot multilayer ensembles (QDMEs), are featured by certain linear sizes and angles of inclination of faces. The structural parameters of such self-organizing nanoobjects govern the electronic and optical performance of related devices and must be controlled easily and reliably. The geometry of nanostructures is related to the materials used and growth conditions and can be controlled in situ to an extent. However, the spread of the average values of geometrical parameters from experiment to experiment may be as high as several tens of percent even if experimental conditions are identical. Therefore, accurate online ex situ (preferably nondestructive) control of basic topological parameters of the structures is central for their characterization.

The methods of transmission electron microscopy (TEM) [1], atomic force microscopy (AFM) [2], and recently near-field scanning optical microscopy (NSOM) [3] have found wide application for analysis of nanodimensional objects; however, as regards detailed structural examination of QD-containing systems, these methods suffer from certain disadvantages. Specifically, the microscopic methods have considerable limitations in determining the averaged and compositional characteristics of nanoobject ensembles. For AFM, these limitations include a small scan area when high lateral and vertical resolutions are required, failure in "looking" into layers, and errors in measuring steep grades and acute angles. The problems inherent in TEM and NSOM are vertical calibration and gaining accurate quantitative characteristics of the QD geometry (including the heights and inclinations of faces) because of diffusion and the need to contrast the image. In addition, the TEM method is destructive and costly.

Application of X-ray radiation, especially its hard range and the short-wavelength part of the soft range, is a general-purpose nondestructive way of examining nanodimensional multilayer structures, specifically, the roughness of interfaces on the atomic scale and interdiffusion at interfaces. The methods of high-resolution X-ray diffractometry (HRXD) and reflectometry (HRXR), which study the distribution of the intensity of the X-ray scattering specular and diffuse components in the straight and reciprocal spaces, provide