ESRF	**Experiment title:** Probing strain evolution in rolled-up semiconductor/shape-memory-alloy tubes by x-ray microdiffraction	**Experiment number**: **MA-2849**
Beamline: ID01	**Date of experiment**: from: 08.04.2016 to: 12.04.2016	**Date of report**: 01.03.2017
Shifts: 12	**Local contact(s)**: Gilbert Chahine	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

Dr. Christian Müller, Technical University of Chemnitz, Measurement and Sensor Technology, Reichenhainer Strasse 70, 09126 Chemnitz, Germany

Prof. Dante H. Mosca, Universidade Federal do Paraná, Departamento de Física, 81531-990 Curitiba, Brazil

Report:

Aims

The aim of the experiment was to investigate the radial lattice-parameter distribution and strain state in rolled-up InGaAs/NiMnGa-tubes by micro x-ray diffraction. These studies should be performed on single rolled-up tubes and on the corresponding flat layers around the (004) reciprocal space position of the InGaAs/NiMnGa -heterostructures. With the knowledge of structural and strain data a better understanding of the material parameters induced by roll-up was expected. In addition, with these knowledge further tuning of material properties towards applications, such as compact on-chip devices, should be feasible.

Experimental

The x-ray microbeam diffraction experiments were performed at an energy E=8 keV. The focussing of the x-ray beam (intensity a few 10^9 photons/s, divergence about 0.01° x 0.05° deg was accomplished using a circular Fresnel zone plate. For the measurements, a 4+2 circle diffractometer with an avalanche photo diode as detector were used, integrating over the investigated angular range in the vicinity of the GaAs (004) and InGaAs (004) peak. The position of the sample was controlled by two orthogonally mounted optical microscopes. The investigated samples are summarized in Tab. 1.

Samples	Type	Substrate	Layer stack
MBE92, grown at 150°C	film	GaAs (100)	AlAs(20nm)/InGaAs(20nm)/NiMnGa(40nm)
MBE92, grown at 150°C	tube	GaAs (100)	InGaAs(20nm)/NiMnGa(40nm)*
MBE94, grown at 150°C	film	GaAs (100)	AlAs(20nm)/InGaAs(20nm)/NiMnGa(40nm)
MBE92, grown at 150°C	tube	GaAs (100)	InGaAs(20nm)/NiMnGa(40nm)*

TABLE. 1 Overview of samples considered for the x-ray microdiffraction experiments. *The tubes typically had ~3 windings.

Results

Firstly, the substrate is aligned in specular diffraction geometry. In this geometry, the incident angle ω (Bragg angle) was set equal to the scattering angle and the detector was positioned at 2θ (Fig. 1(a)). The selected tube is optically prealigned with the tube axis perpendicular to the incoming x-ray beam. From the diffraction performed around the InGaAs (004) clearly the tube position can be determined (Fig. 1(b)), which is in agreement with the optical microscopy image (inset of Fig. 1(b)).

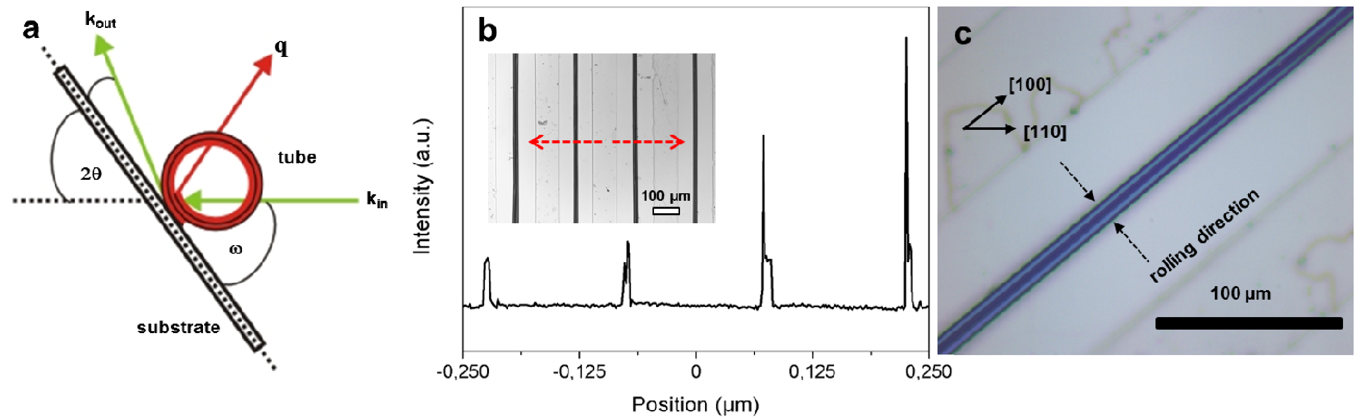

FIG. 1 (a) X-ray diffraction of rolled-up InGaAs/Ni-Mn-Ga tubes. (b) Comparison of x-ray measurement and optical microscopy for detremination of tube position. (c) Detailed optical microscopy image of the investigated double tubes.

Secondly, $\omega/2\theta$ scans were performed on the samples listed in Tab.1. Thereby the initial film and the corresponding tubes were analyzed. The diffraction scan clearly show the presence of GaAs (004) and InGaAs (004). However, NiMnGa was not detected, due its nanocrystalline nature (found by transmission electron microscopy, not shown). Consequently only the InGaAs (004) can be used for further strain analysis. Due to lattice mismatch (3%) between GaAs and InGaAs a compressive strain is confirmed in the original film. After roll-up a small up-shift of the InGaAs (004) peak can be observed, which amounts to ~0.1° respectively for MBE92 and MBE94. These shift may indicate a small strain release of ~0.3%.

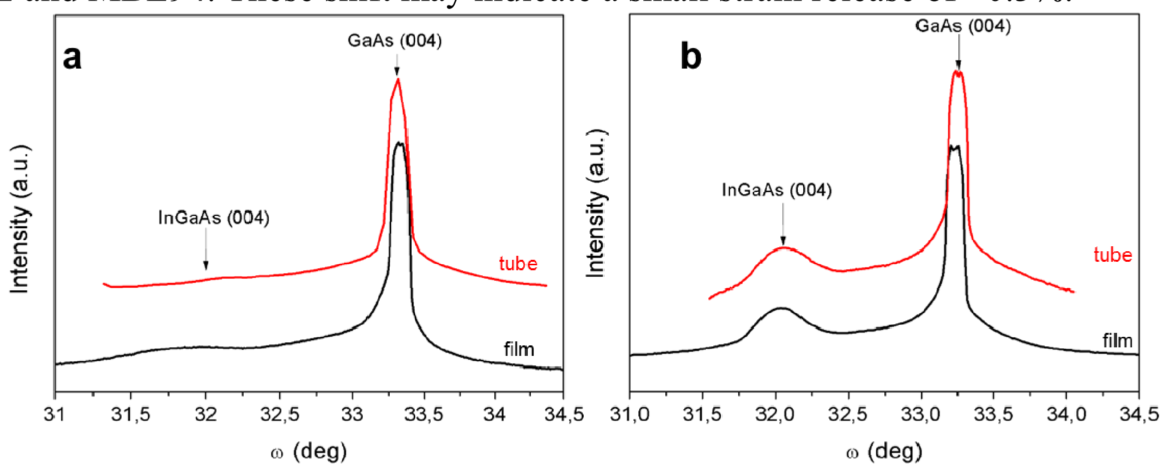

FIG. 2 X-ray diffraction (ω/2θ scans) of InGaAs/Ni-Mn-Ga film and the corresponding rolled-up tube: (a) Sample MBE92 (b) Sample MBE94.

Finally, the K-map principle was applied on our sample in order to visualize the X-ray intensity at a certain Bragg position and to allow later the three-dimensional reciprocal space mapping including strain analysis. For K-mapping a selected area of the rolled-up tubes (Fig. 3, investigated tube comparable with Fig. 1(c)) was scanned at different ω (31.60°-32.60°, step size 0.03°), while the detector position was not changed (2θ = 63.79°). The two tube can be clearly distinguished from background due the good crystallinity of InGaAs correlating with a high X-ray intensity. In addition, structural inhomogeneities and strain hetereogeneities can be identified at the boudary between neighbouring tubes and at the rolling edge of the tube. The images also show a small area of unrolled filmed between the tubes. The strain analysis is still in progress.

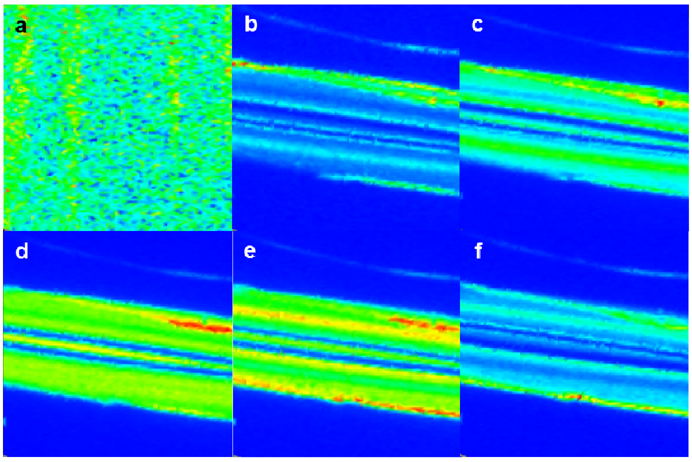

FIG. 3 Two-dimensional plot of the integrated X-ray diffraction of a rolled-up double tube around the (004) InGaAs Bragg position: InGaAs/Ni-Mn-Ga tubes. (a) ω = 31.65°, (b) ω = 31.77°, (c) ω = 31.97°, (d) ω = 32.17°, (e) ω = 32.37°, (f) ω = 32.57°.