Characterization of Nanowires

M. Keplinger[1], D. Kriegner[1], B. Mandl[1, 2], J. Stangl[1], V. Chamard[3], E. Wintersberger[1], R.T. Lechner[1], D. Hufnagl[1], and G. Bauer[1]

[1] Institut für Halbleiter- und Festkörperphysik, Johannes Kepler Universität Linz, Altenbergerstrasse 69, 4040 Linz, Austria
[2] Solid State Physics, Lund University, Professorsgatan 1, 22100 Lund, Sweden.
[3] Université P. Cezanne Aix-Marseille III, CEDEX 20, 13397 Marseille, France.

Semiconductor nanowires have attracted attention in recent years due to their unique electronical and structural properties. Such structures provide one-dimensional electronic material and the possibility to connect single quantum dots, which are zero-dimensional electronic structures. In addition, nanowires exhibit interesting mechanical properties which make new, so far not studied combinations of materials possible. The most significant demonstration of this possibility is the growth of III-V nanowires on Si substrates [1], [2]. Since such structures are interesting for fundamental science as well as for applications, a thorough study of the material properties and the material quality is needed. We show x-ray techniques for nanowires analysis, to investigate epitaxial orientation of the wires, chemical composition, and crystal structure (zinc-blende, wurtzite) of nanowires.

Introduction

The nanowires are grown in a low pressure metal organic vapor phase epitaxy system, mainly using a gold-free nucleation process for $InAs_{1-x}P_x$, and a gold nucleation center for InP nanowires. In both cases, hexagonal wires grown in [111] direction perpendicular to the sample surface are obtained. Figure 1 gives an impression of the nanowire shape and arrangement from scanning electron microscopy. The results of x-ray characterization on these nanowires are presented in the following.

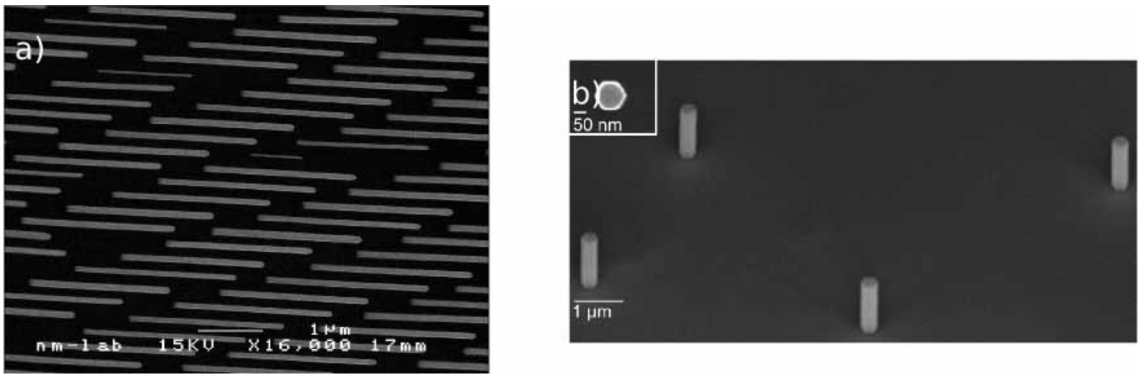

Fig. 1: (a) InAs nanowires grown on a pre-structured InP (111)B substrate. Image tilted by 45°. (b) InAs nanowires randomly nucleated on an InP (111)B substrate. Image tilted by 45°. Inset: top view of a nanowire, showing its hexagonal shape.

P Concentration of InAsP Wires from High Angle X-Ray Diffraction

InAsP nanowires were grown at constant PH flow and temperatures from 520 to 640 °C on an InP (111)B substrate. The wires grow in [111] direction and therefore perpendicular to the substrate surface.

Asymmetric high angle x-ray diffraction maps around the (224) peak of InP were measured to determine the As content and degree of relaxation of the wires. The measurements were performed at the Seifert XRD 3003 laboratory source. Reciprocal space maps (RSM) of two samples grown at different temperatures are shown in Fig. 2 (a) and (b). The reference sample in (a) was grown at zero PH flow.

For a series of samples the As content was determined and plotted against the growth temperature (c). From the RSM it is obvious that the grown wires are relaxed to their bulk lattice parameter. Furthermore, we see that the P content increases with increasing growth temperature. In this way a P content from 13% to 24% could be realized.

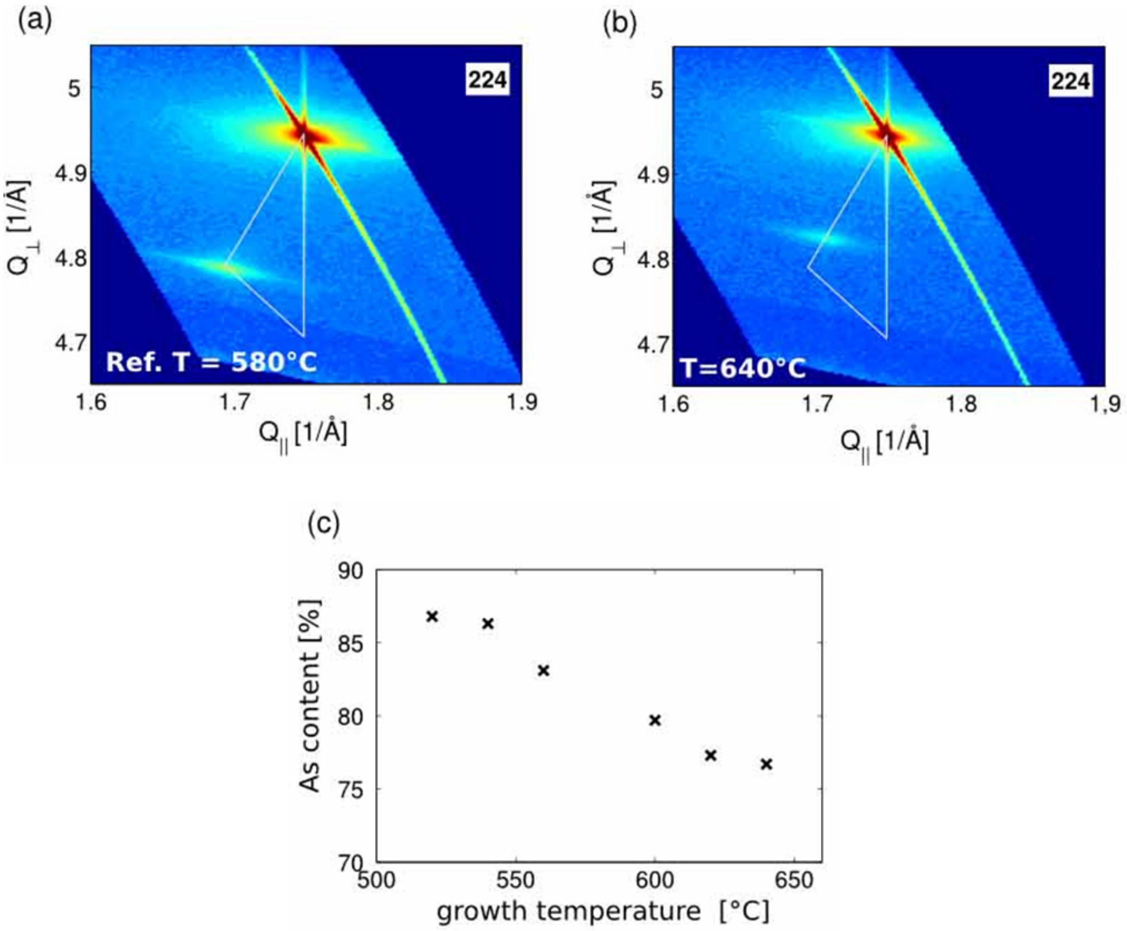

Fig. 2 (a) and (b): RSMs around the (224) Bragg peak of samples with different growth temperatures. (c): Deduced As content, plotted over different growth temperatures. The white triangle denotes possible peak position due to the InAsP wires, depending on P content and strain state.

Wurtzite to Zinc-Blende Ratio in Wire Ensembles

Although for the nanowire material in bulk form zinc-blende (ZB) is the stable crystal structure, in nanowires also wurtzite (WZ) lattice is observed. This differs from the zinc-blende only by a change of the stacking sequence along the growth direction from ABC to AB. To characterize the amount of WZ lattice, we used the fact that for x-ray diffraction some Bragg reflections are equivalent, i.e. occur at the same position in reciprocal space for both lattices, while others exist only in the WZ crystal structure. From the comparison of the integral intensities of several reflections with the theoretical values, and considering all experimental factors such as the change of illuminated area for different Bragg angles, we can derive the wurtzite concentration in a wire ensemble as sketched in Fig. 3.

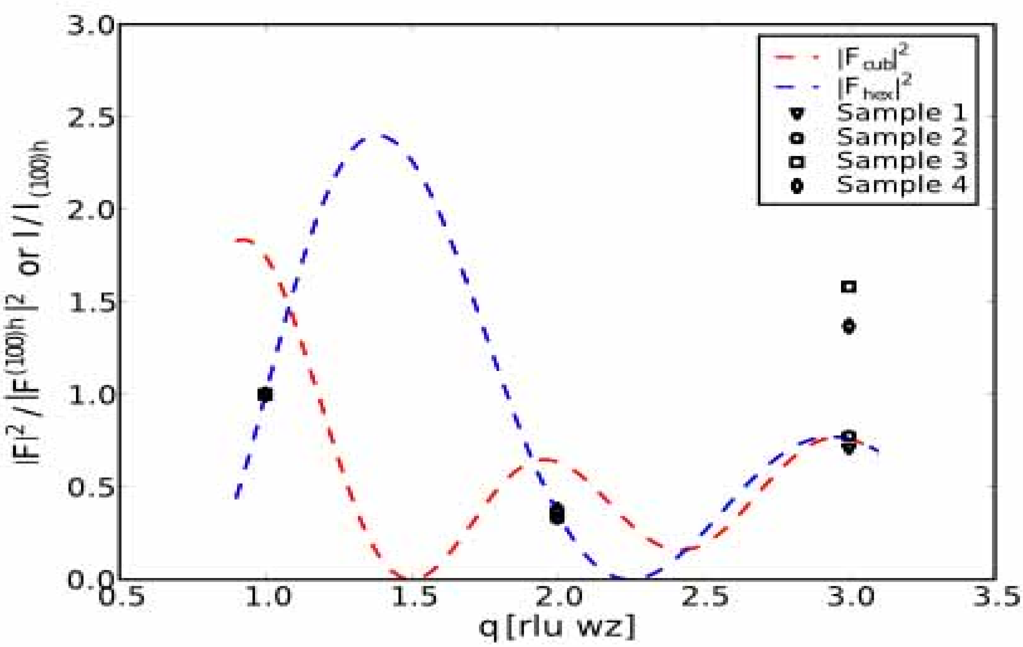

Fig. 3: Normalized intensities of (10-1.0), (20-2.0), and (30-3.0) WZ reflections. The lines between the peaks are continuous interpolations of the structure factor. (30-3.0) of WZ is equivalent to (22-4) of ZB, hence the additional intensity at the Bragg peak is due to the ZB part of the nanowires.

Single Wire Characterization

Since in the WZ/ZB ratio determination for a large nanowire ensemble illuminated by the x-ray beam it cannot be decided whether each wire contains ZB and WZ segments, or some wires are purely ZB while other grow purely in the WZ lattice, we used focused x-rays to illuminate only few nanowires with a focused, partly coherent beam. Measurements were performed at beamline ID01 at the ESRF, Grenoble [3]. The measurements shown in Fig. 4 exhibit a speckle pattern in the intensity distribution, due to the interference of the scattering amplitudes of individual WZ segments. From that the nanowire properties are inferred:

- Three almost isolated peaks are observed at the (30-3.0) reflection, where wurtzite and zinc-blende components are not distinguished, and a “large” structure (the whole nanowire) scatters.

- Broad features are observed at the (10-1.0) reflection, where only wurtzite parts scatter, indicating that the individual scattering objects are small.

To verify this result the intensity distribution was simulated using a model consisting of three basically zinc-blende nanowires, each with randomly distributed, on average 6 nm long wurtzite segments. From the simulation this segment-like wurtzite distribution along the wires can be proven, and the average wurtzite content and segment length determined.

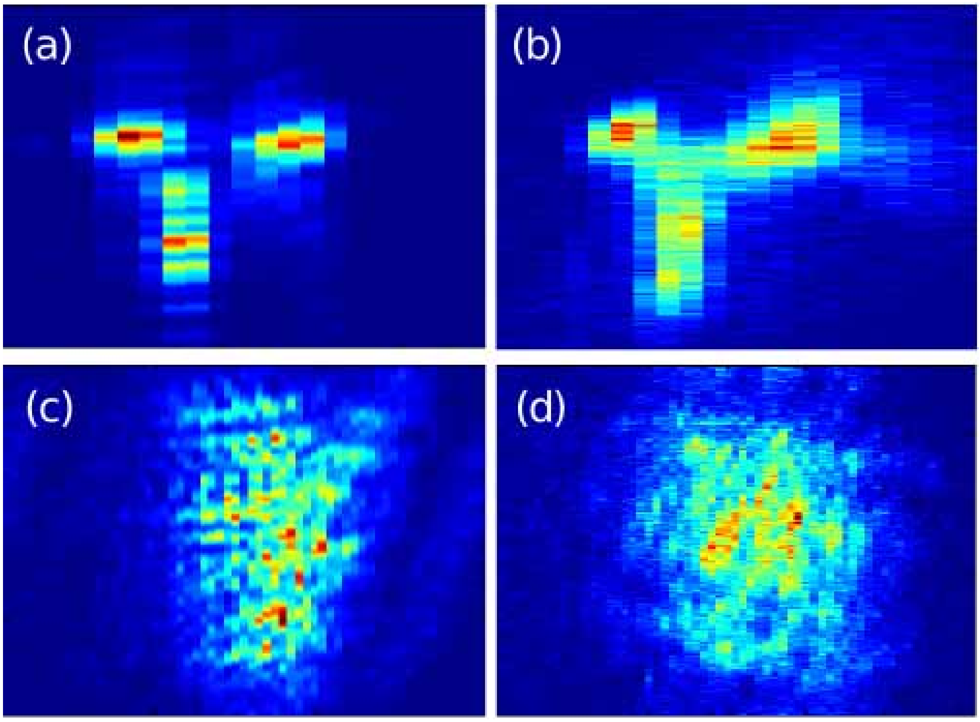

Fig. 6: (a) simulation, (b) measurement of the (30-3.0) peak; (c) simulation, (d) measurement of the (10-1.0) peak of three InAs nanowires

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References

[1] B. Mandl, J. Stangl, T. Martensson, A. Mikkelsen, J. Eriksson, L. S. Karisson, G. Bauer, L. Samuelson, and W. Seifert, Nano Letters **6**, 1817 (2006).

[2] T. Martensson, J. B. Wagner, E. Hilner, A. Mikkelsen, C. Thelander, J. Stangl, B. J. Ohlsson, A. Gustafsson, E. Lundgren, L. Samuelson, et al., Advanced Materials **19**, 1801 (2007).

[3] V. Chamard, J. Stangl, S. Labat, B. Mandl, R. T. Lechner, and T. H. Metzger, J. Appl. Cryst. **41**, 272 (2008).