Low Dimensional Nanostructures Grown by Molecular Beam Epitaxy

P. Klang, H. Detz, A.M. Andrews, B. Basnar, W. Schrenk, A. Lugstein, and G. Strasser

Center for Micro- and Nanostructures, Vienna University of Technology,
Institute for Solid-State Electronics, Vienna University of Technology,
Floragasse 7, Vienna, Austria

Introduction

Self-assembled semiconductor quantum dots (0-D system) have attracted researchers for more than 20 years, because of their unique electronic and optoelectronic properties based on reduced dimensionality. In the last several years, 1-D nanowires have entered the field of nanoscale devices. We present the growth and characterization of these low dimensional structures grown by a solid-source molecular beam epitaxy (MBE) system.

Quantum Dots

For the 0-D structures, we focus on the growth of high quality InAs quantum dots (QDs) in an $Al_xGa_{1-x}As$ matrix for prospective incorporation into intersubband devices like MIR detectors, THz detectors and quantum cascade lasers (QCLs). The growth temperature, growth rate and deposited InAs layer thickness are key parameters to control QD energy levels. For QCLs based on the $Al_xGa_{1-x}As$/GaAs material system, we need the QD ground state energy above GaAs conduction band edge and a narrow size distribution of the QDs.

Growth Parameters

To decouple the density and size of the QDs we use a low InAs growth rate, below 0.01 µm/h. At this low growth rate, the density depends mainly on the growth temperature, and the size of the QDs is controlled by the deposited InAs thickness. The Al content of the growth surface also influences the QD properties. For a higher Al concentration the QD density is increased while the QDs size is reduced. QDs grown on $Al_xGa_{1-x}As$ surfaces also have a greater inhomogeneous size distribution. The sample surface morphologies were analyzed by atomic force microscopy, where we obtained QD density, QD height and its standard deviation, and an estimate of the volume of InAs incorporated into the QDs and the remaining InAs volume in the wetting layer.

Calibrating InAs Growth Rate

The InAs deposition rate was calibrated by high-resolution x-ray diffraction (XRD) measurements of a strained $In_xGa_{1-x}As$/GaAs superlattice (see Fig. 1). The thickness and therefore the growth rate of the GaAs and InAs can be independently determined using this technique.

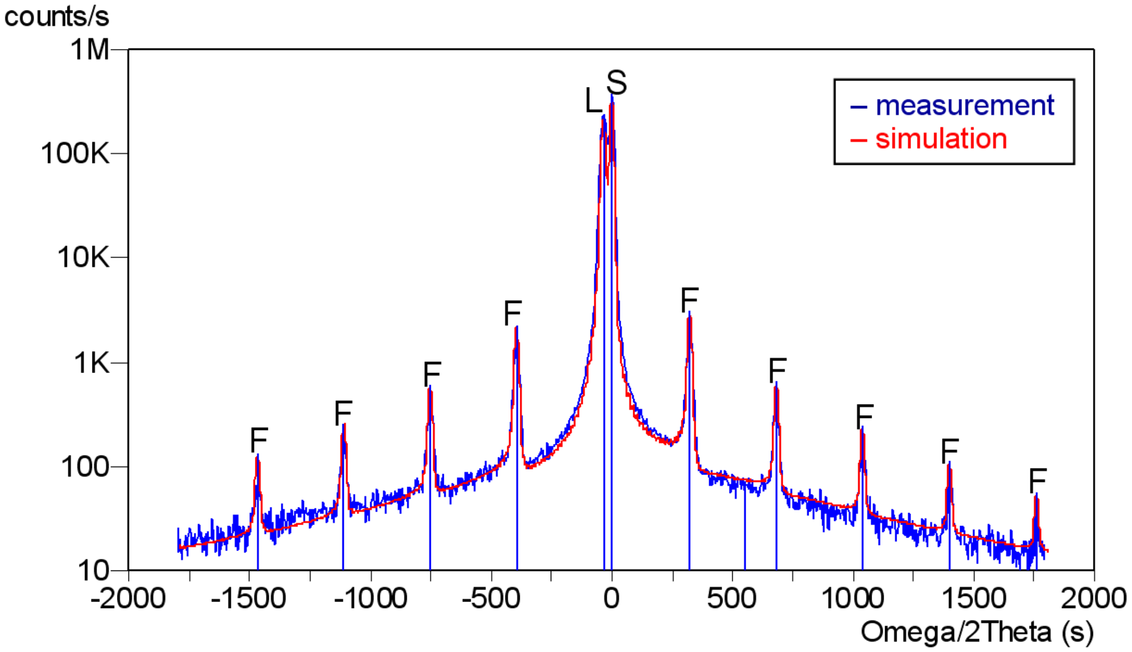

Fig. 1: Measured (blue) and simulated (red) rocking curve around the 004 diffraction for $In_xGa_{1-x}As/GaAs$ superlattice. The layer peak (L) is shifted to left from the substrate (S) GaAs peak, fringe peaks (F) are equidistantly spaced.

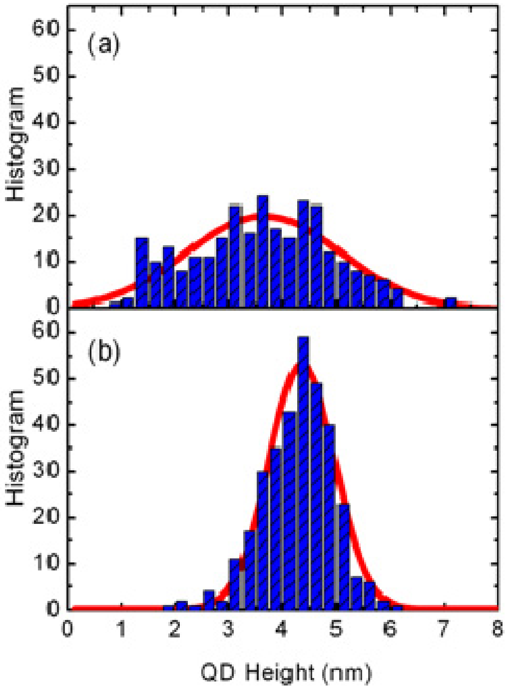

Fig. 2: QD size distribution for (a) standard and (b) new recipe with lowering the As_4 flux during the QDs growth. The standard deviation of the QDs height was reduced more than three times.

Improving Size Distribution

Lowering the As_4 flux during the QDs growth was found to dramatically improve the QD size distribution. For QDs grown on a 45% $Al_xGa_{1-x}As$ surface the standard deviation of the QDs height was reduced from 2.1 nm to 0.6 nm (Fig. 2).

III-V Self-Assembled One-Dimensional Nanowires

We study the MBE growth of III-V self-assembled one-dimensional nanowires on Si nanowires originally grown by low-pressure chemical vapor deposition. To understand the growth mechanism, GaAs growth rates were varied from 0.1–0.55 µm/h and various V/III ratios were used to deposit equivalent layer thicknesses ranging from 40 – 200 nm. Additionally, we investigated MBE growth of GaAs nanowires on different Si substrates with Au catalysts and with various pre-growth surface treatments using buffered HF. The samples were analyzed by scanning electron microscopy (SEM), photoluminescence measurements, high-resolution transmission electron microscopy (TEM) and XRD analysis.

XRD Spectra

There are both powder diffraction peaks and the monocrystalline peaks in the reciprocal space map of NWs measured by high-resolution x-ray diffraction. There are peaks from the monocrystalline Si substrate and also from the epitaxial Si NWs, and polycrystalline peaks from both zinc-blende and wurtzite GaAs, the Au catalyst, and the AuGa alloy (Fig. 3). There was no observed peak for the expected AuSi alloy at the tip of the Si NWs.

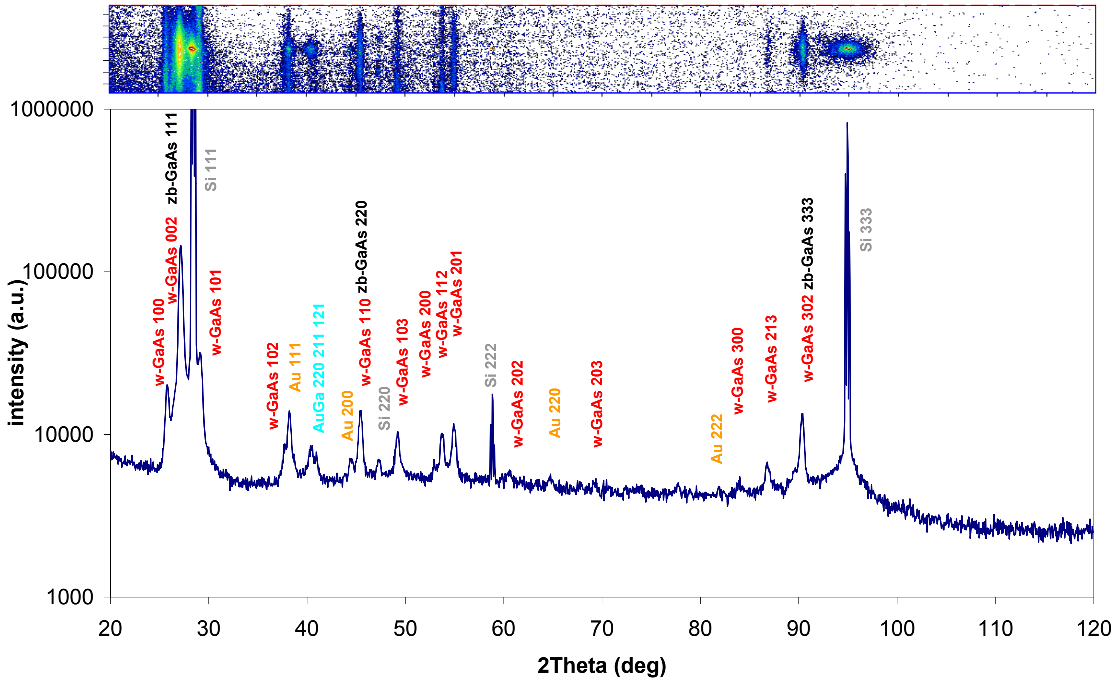

Fig. 3: XRD reciprocal space map and spectra measured on the tree-like structures of GaAs NWs on Si NWs.

SEM Results

Using SEM we can see GaAs nanowhiskers forming structures with a 6-fold symmetry on the Si NW. The length of the Si nanowire trunks are 2 µm. The diameter of the Si trunk is determined by the 80 nm diameter of the Au catalyst. The length of the nanowhiskers (100 nm – 5 µm) depends on the amount of deposited GaAs. GaAs nanowhiskers can be found at any position along the side of the Si-NW trunk (see Fig. 4).

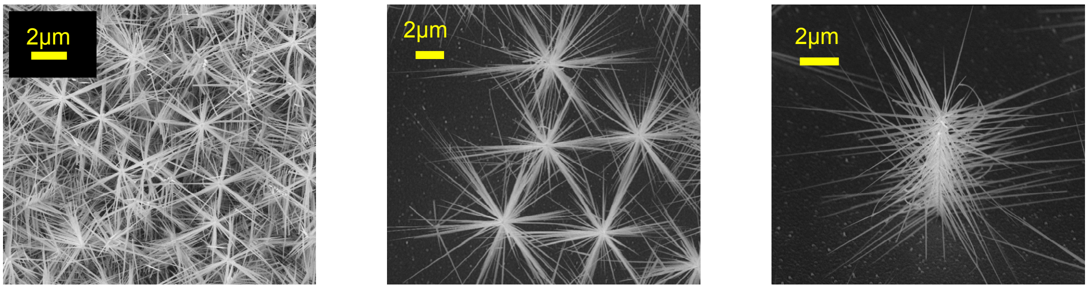

Fig. 4: SEM images of the GaAs nanowhiskers grown on Si NW trunks forming 6-fold tree-like structure.

GaAs NWs on Si Substrates

For a better understanding of crystal properties of the GaAs nanowhiskers, the growth of the GaAs nanowires on planar Si wafer with various pre-growth surface treatments was investigated. We observed high density oriented GaAs nanowires on Si (112) substrates which were exposed to HF after the deposition of the Au catalyst layer. From the SEM analysis of the cleaved edge these nanowires appear tilted under an angle of 19.5° from the substrate normal. This tilt corresponds to the angle between [112] and [111] direction. High-resolution TEM analysis confirmed that the GaAs [0001] nanowires were grown in the wurtzite crystal structure along the Si [111] direction.

Acknowledgements

We acknowledge partial support by the following projects and agencies next to GMe: IRON, MNA, PLATON, and SANDIE.

References

[1] A. Lugstein, A.M. Andrews, M. Steinmair, Y. Hyun, E. Bertagnolli, M. Weil, P. Ponratz, M. Schramböck, T. Roch, G. Strasser, *Nanotechnology*, **18**, (2007)

[2] H. Detz, P. Klang, A.M. Andrews, A. Lustein, M. Steinmair, Y.J. Hyun, E. Bertagnolli, W. Schrenk, G. Strasser, *Journal of Crystal Growth*, **311**, (2009)