Electron microscopy of nano-inclusion formation in (Ga,Mn)As magnetic semiconductors

A. Kovács¹, T. Kasama¹, J. Sadowski²,³, J. Domagala³, R. Mathieu⁴, R. E. Dunin-Borkowski¹ and T. Dietl¹,⁵

¹Center for Electron Nanoscopy, Technical University of Denmark, Kgs. Lyngby 2800, Denmark
²MAX-Lab, Lund University, P.O. Box 118, 221 00 Lund, Sweden
³Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warszawa, Poland
⁴Department of Engineering Sciences, Uppsala University, P.O. Box 534, SE-751 21 Uppsala, Sweden
⁵Institute of Theoretical Physics, University of Warsaw, PL-00-681 Warszawa, Poland

The origin of ferromagnetism in transition metal (TM) doped semiconductors is still poorly understood. Recent studies [1] have underlined the need to study the incorporation of magnetic ions into the host lattice at the nanoscale, in order to establish whether the material is truly a diluted magnetic semiconductor, whether magnetic dopants aggregate to form coherent TM-rich regions, or whether nanocrystals that contain secondary magnetic phases are present.

Here, we study the transition from a diluted (Ga,Mn)As magnetic semiconductor (0.5 at.% Mn) to a phase-segregated microstructure upon annealing to 630°C. We use a range of transmission electron microscopy (TEM) techniques to study the local structural, chemical and magnetic properties of epitaxial (Ga,Mn)As layers grown on GaAs by molecular beam epitaxy. Aberration corrected high-resolution TEM images and nano-beam diffraction patterns from individual precipitates are used to show that both cubic (zinc blende) and hexagonal (NiAs-type) crystals form with sizes of 8 to 16 nm. High-angle annular dark-field TEM images and electron energy-loss spectroscopy are used to show that local density fluctuations are present adjacent to the Mn(Ga)As nanoparticles. We propose that these regions are voids. We also use in situ annealing to follow the phase transformation directly in the electron microscope.

This work was supported by the FunDMS Advanced Grant of the European Research Council within the “Ideas” 7th Framework Programme of the European Comission.