Magnetic and structural properties of MBE grown wurtzite (Ga,Mn)As shells in a radial quantum well nanowire heterostructures

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Investigation of (Ga,Mn)As ferromagnetic semiconductor in a form of quasi 1-dimensional nanostructures is important in the context of ferromagnetic nanowires which were proposed as a base for a new type of nano-magnetic memory structures [1] and magnetic logics [2] manufactured from nanowire grids [3]. Conditions required to prepare a ternary (Ga,Mn)As alloy, which are dictated by low temperature MBE growth are in contradiction to the growth procedure of metal-induced formation of NWs. Hence, the only way to produce (Ga,Mn)As in a nanowire geometry can be realised as a shell deposited on a beforehand grown semiconductor core nanowire templates. Here, in order to additionally tune the magnetic anisotropy by strain, cores made from (In,Ga)As alloy were chosen. Variation of In concentration in the core allows to achieve desired strain state in the shell. In addition, the presence of In in the cores not only determines strain, but also induces wurtzite crystalline structure, which is inherited by magnetic (Ga,Mn)As shells. However, in earlier studies we found that such core-shell NWs lack a long-range magnetic order and magnetically behave as super-paramagnets [4], despite, 5 % of Mn content, what is more than sufficient to induce ferromagnetism in planar (Ga,Mn)As. We attribute this behaviour to a lack of itinerant holes, which mediate the long-range ferromagnetic interactions. Assuming that the shell growth is optimised to obtain both smooth morphology and the lowest concentration of defects while keeping the highest amount of Mn possible, the lack of the mobile holes was attributed to their out diffusion towards the core and/or to the surface depletion. To counter act these effects, NWs with high temperature $Al_{0.4}Ga_{0.6}As$ or low temperature grown GaAs post-growth annealed at 600 ^{o}C in order to create metallic As nanoclusters pinning the Fermi level in the middle of the GaAs band-gap [5] barriers for holes between the $In_{0.2}Ga_{0.8}As$ core and the $Ga_{0.95}Mn_{0.05}As$ shell were prepared. The high crystalline quality of these multi-shells of NWs has been confirmed by dedicated XRD for the ensembles of NWs and high resolution TEM studies of individual NWs in two geometries: cross-sectional and perpendicular to the side facets. For these NWs a weak spontaneous magnetisation has been observed below 24 K during a cool down from high temperatures, which is the first such observation in the MBE grown NWs with (Ga,Mn)As shells - a form different than planar epilayer. By comparing these results with our previous findings [4] we can conclude that in the re-designed NWs we literally witness the birth of the long range FM order, which is just surfacing from the still (present) overwhelming SP component.

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