Magnetic properties of MBE grown (In,Ga)As-(Ga,Mn)As core-shell nanowires

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Quasi 1-dimensional nanostructures fabricated from (Ga,Mn)As) ferromagnetic semiconductor are interesting in the context of ferromagnetic nanowires (NWs) which have been proposed as base of a new type of nano-magnetic memory structures [1]. The specific preparation conditions of (Ga,Mn)As ternary alloy (MBE growth at low temperatures) are not compatible with the parameters of catalyst-induced formation of GaAs NWs [2]. Thus, to obtain (Ga,Mn)As in NW geometry, core-shell structures have to be fabricated, where primary NW cores and magnetic (Ga,Mn)As NW shells are grown at high and low temperature, respectively. In order to tune the magnetic anisotropy of (Ga,Mn)As shells (determined mainly by strain) we have chosen the ternary (In,Ga)As alloy as the NW core material. By altering the composition of (In,Ga)As core the desired strain state of (Ga,Mn)As shell can be attained. Moreover, (In,Ga)As in the NW core can grow either in zinc-blende or wurtizite crystal structure, which is then inherited by (Ga,Mn)As shell.

The NWs investigated here have been obtained by Au-catalyst induced MBE growth on GaAs(111)B substrates. The (In,Ga)As NW cores were grown at 500 °C, subsequently the (Ga,Mn)As shells were deposited at low temperature (below 250 °C). Scanning and transmission electron microscopy investigations of NWs, revealed wurtzite monocrystalline structure of the whole stack with NW axes oriented along [0001] direction and side facets of (11-20) orientation. On average, the NWs have diameters of about 70 nm and lengths of up to 3 μm (see Fig.1).

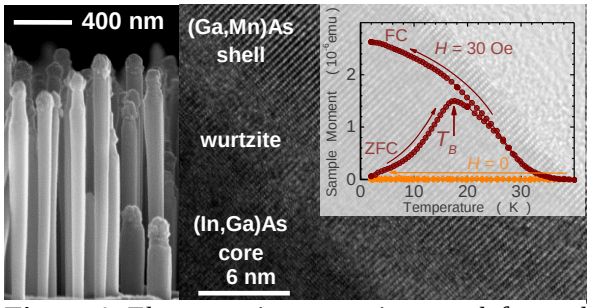

Figure 1. *Electron microscopy images: left panel - SEM, right panel - high resolution TEM; of Au-catalysed (In,Ga)As-(Ga,Mn)As core-shell nanowires. The inset to the right panel shows temperature dependent magnetic moment of the NWs embedded in the PMMA resist and separated from the growth substrate.*

Magnetic properties of NWs ensemble were studied by SQUID magnetometry revealing the presence of ferromagnetic coupling below about 30 K and only moderate magnetic anisotropy with the magnetic easy axis oriented along the normal to NWs side facets. However, the coupling is found only to be effective on mesoscopic scales, so as the ensemble, the NWs exhibit blocked superparamagnetic properties, as indicated in the inset to Fig. 1. The lack of a long range coupling in the (Ga,Mn)As shell is probably due to the low hole density which might have resulted from an out-diffusion of holes from the shell into to the lower energy gap (In,Ga)As core, and/or due to the surface depletion layer being comparable to the shell thickness. The low hole density makes the fluctuations of the local density of states relevant resulting in the mosaic regions with enhanced (magnetically coupled) and reduced (paramagnetic) hole densities.

[1] M. Hayashi et al., *Science* **320**, 209 (2008).
[2] J. Sadowski et al., *Nano Lett.* **7**, 2724 (2007).