Application Note CI35

Magnetoresistance of self-assembled GaMnAs based nanowires using the atto3DR

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Introduction

Dilute magnetic semiconductors promise to offer a rich playground for designing spintronics devices, i.e. solid state based electronics, which not only make use of the electron's charge, but also the spin degree of freedom. In particular the relatively new class of self-assembled ferromagnetic nanowires could potentially be used for producing e.g. one-dimensional spin valve transistors or ferromagnetic single electron transistors, while maintaining a high flexibility in the choice of material as well as the axial and radial degrees of freedom. Due to the arbitrary orientation inherent to self-assembled materials on the substrate, typical characterization techniques such as magnetoresistance measurements conducted at cryogenic temperatures greatly benefit from the possibility to freely change the mutual orientation of external magnetic field and sample. Although this is easily possible e.g. by using a 3D vector magnet setup, the associated costs (>> 100 k$) are often prohibitive. Single axis sample rotator setups on the other hand not only require choosing either an out-of-plane or in-plane configuration prior to cooldown, but also put firm restrictions on certain measurements which rely on a precise orientation of the field e.g. perpendicular or parallel to an initially unknown direction along a sample structure. The perfect solution to such applications is now available (at moderate costs) by the new atto3DR, attocube's 3-dimensional rotator [1].

Experimental Setup

The atto3DR setup is shown above as well as sketched in Figure 1. The module consists of two piezo based 'slip-stick' rotators, which by their combination allow for arbitrary mutual orientations of an external magnetic field vector (e.g. from a standard single solenoid superconducting magnet as present in most low temperature cryostats) and the sample plane. The first rotator essentially controls the out-of-plane (θ) component, whereas the second rotator revolves around an axis perpendicular to the sample plane, and thus affects the in-plane component. The atto3DR comes fully wired with 20 measurement lines as twisted pairs, a convenient leadless ceramic chip carrier (LCCC) mount for quick and easy sample exchange of wire bonded sample structures (based on non-magnetic pogo pins), and two resistive encoders for the rotators so that full closed loop operation is possible.

The corresponding electronics ANC350 can easily be integrated with automated measurement routines via a LabVIEW® interface or a DLL.

Figure 1: *Working principle. The first rotation axis controls the orientation of the sample plane with respect to the fixed external magnetic field (ϑ: ± 90°), whereas the second rotator actuates the in-plane component (φ: ± 90°). Combining both axes allows for arbitrary mutual orientations of the magnetic field vector with regards to the sample plane.*

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Measurements

Similar to a recent publication by C. H. Butschkow and co-workers from the group of Prof. Dieter Weiss (Univ. of Regensburg) [2], magnetotransport measurements on individual GaAs/(Ga,Mn)As core-shell nanowires have been conducted. The nanowires were grown self-assembled via molecular-beam-epitaxy (MBE) and the vapor-liquid-solid technique (VLS) using gold as catalyst. The (Ga,Mn)As shell was grown

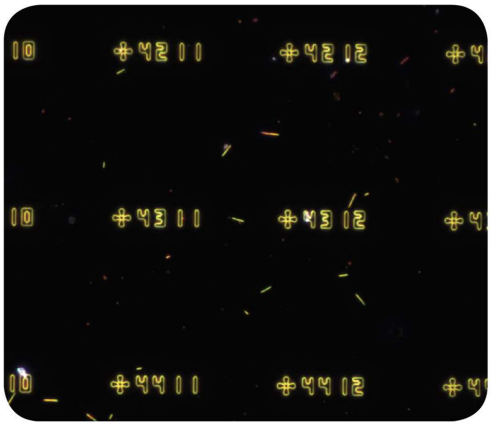

Figure 2: *Dark field microscope image of randomly distributed GaAs/(Ga,Mn)As core-shell nanowires on a SiO_2 substrate with pre-patterned marker structures.*

epitaxially on the side facettes with a Mn concentration of approximately 5% [3]. In order to contact individual nanowires (diameter ≈ 100 nm, length ≈ 4 µm) electrically, they were transferred by casting a droplet of nanowire suspension onto a SiO_2 substrate, leading to a random distribution of nanowires (see Figure 2). Gold contacts (width ≈ 300 nm, thickness ≈ 200 nm) were fabricated on selected nanowires (see Figure 3) using electron beam lithography.

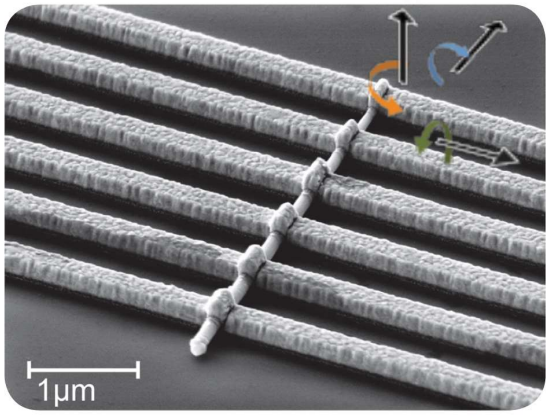

Figure 3: *Tilted scanning electron micrograph of a contacted nanowire. Black arrows indicate the sample coordinate system. Coloured arrows indicate the rotational directions as used in the measurements in Figure 5 (blue: transverse, orange: in-plane, green: perpendicular rotation).*

A detailed description of the sample-preparation can be found in [2]. For this experiment, we measured the resistance in a two-terminal configuration at a cryogenic temperature of 4 K. From previous measurements, it is known that the contact resistances can be considered as negligible and two terminal resistance measurements are in many cases sufficient. The (Ga,Mn)As shell shows a ferromagnetic transition temperature of ~20 K and strong uniaxial magnetic anisotropy with the magnetic easy axis pointing along the nanowire axis. The external magnetic field needed to force the magnetization entirely into the magnetic hard axis, usually referred to as anisotropy field H_a, is in the range of $\mu_0 H_a$ = 1.3 T to 2 T. This value exceeds the anisotropy field of comparable (Ga,Mn)As nanostructures by a factor of 10 [4, 5]. As described in [2], this large anisotropy field leads to a significant dependency of the charge-carrier magnon scattering resistance contribution on the direction of the magnetization. In particular, we found that the magnetoresistance of the nanowires is for relatively small magnetic fields at least to the first order linearly proportional to the internal effective magnetic field H_{eff}, rather than the external field H_0:

$$\boldsymbol{R} \sim -|H_{eff}| \qquad (1)$$

This effective magnetic field contains, additionally to the external field, any molecular fields. Since the saturation magnetization in (Ga,Mn)As is low, the demagnetizing field can be neglected and only the anisotropy field has to be considered. It can be shown, that H_{eff} is approximately described in our case by:

$$H_{eff} = H_0 \cos(\phi_M - \phi_H) + H_0 \cos(2\phi_M) \qquad (2)$$

with ϕ_M and ϕ_H denoting the directions of the magnetization and the external magnetic field H_0 with respect to the magnetic easy axis, respectively. Together with eq. 1, the angular dependence of H_{eff} leads to a dependency of the magnetoresistance on the direction of the magnetization and thus enables us to gain knowledge of the magnetic anisotropy by means of (longitudinal) resistance measurements.

This dependency can be measured by rotating the nanowire in a large affixed magnetic field, thus varying ϕ_H and forcing the internal magnetization roughly into the direction of the external field. Figure 4 shows such measurements for 3 different values of H_0, revealing very pronounced magnetoresistance. It can be seen that the amplitude of the magnetoresistance on the scale of Figure 4 decreases with increasing external magnetic field, since then the first term in eq. 2, which can be regarded for high magnetic fields as a constant offset, becomes dominant.

The homogeneity and pureness of the uniaxial magnetic anisotropy of a nanowire can be examined by performing this measurement for different rotation planes. However due to the random distribution of the nanowires on the substrate, the implementation of such an experiment is in general not straight

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forward. Using the convenience of a double rotator as the atto3DR, this is easily realizable in this setup.

We performed magnetoresistance measurement as a function of the field angle for three different rotation planes (see Figure 5):

(i) in-plane rotation, referring to the SiO_2 substrate plane
(ii) out of plane (perpendicular) rotation with the long nanowire axis entirely in the rotation plane
(iii) out of plane (transversal) rotation with the rotation plane transversal to the nanowire axis

The in-plane and the perpendicular magnetoresistance traces exhibit approximately the same amplitude, which is an indication that only the uniaxial anisotropy along the nanowire axis is present. The shift of 20° of the in-plane trace along the angular scale compared to the perpendicular trace is related to the random orientation of the nanowire.

While the in-plane and the perpendicular measurements show rather pronounced magnetoresistance, the resistance change for transverse rotation is almost negligible. This is expected, as then the magnetization is always forced in the magnetic hard direction (ϕ_M = 90°) resulting in a constant effective magnetic field.

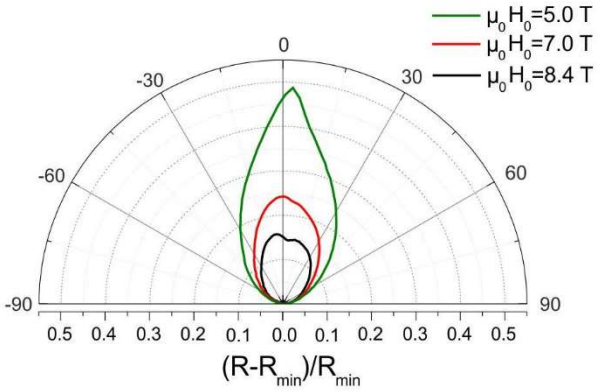

Figure 4: *Normalized magnetoresistance as a function of the angle between externally applied magnetic field and the nanowire axis for various magnitudes of the external magnetic field.*

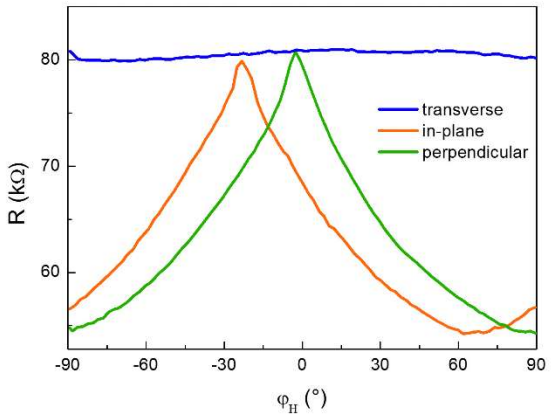

Figure 5: *Magnetoresistance at 5 T as a function of the angle between externally applied magnetic field and the nanowire axis for different rotation planes: (orange) in-plane rotation, referring to the SiO_2 substrate plane, (green) out of plane (perpendicular) rotation with the long nanowire axis entirely in the rotation plane, and (blue) out of plane (transversal) rotation with the rotation plane transversal to the nanowire axis.*

References

[1] www.attocube.com/attoCRYO/atto3DR.html
[2] C. H. Butschkow, E. Reiger, S. Geißler, A. Rudolph, M. Soda, D. Schuh, G. Woltersdorf, W. Wegscheider, D. Weiss, arXiv:1110.5507v1
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The sample was prepared by C. H. Butschkow et al. The measurements were performed in attocube application labs by C. H. Butschkow and F. Otto, 2012.