phys. stat. sol. (a) **203**, No. 14, 3597–3601 (2006) / **DOI** 10.1002/pssa.200622388

Transport through (Ga,Mn)As nanoconstrictions

Markus Schlapps[*], **Matthias Doeppe, Konrad Wagner, Matthias Reinwald,**
Werner Wegscheider, and **Dieter Weiss**

Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Universitätsstraße 31,
93040 Regensburg, Germany

Received 13 April 2006, revised 1 June 2006, accepted 14 June 2006

PACS 72.25.Dc, 73.63.–b, 75.30.Gw, 75.47.–m, 75.50.Pp

We investigate magnetoresistance effects for transport across (Ga,Mn)As nanoislands, detached by nanoconstrictions from wider (Ga,Mn)As input leads. As in previous studies a huge magnetoresistance was found for nanoconstrictions in the tunnelling regime. For slightly wider junctions an enhanced anisotropic magnetoresistance effect was observed.

The discovery of a very large tunnelling magnetoresistance (TMR) for transport through lateral ferromagnetic (Ga,Mn)As wires with nanoconstrictions came as a surprise [1]. In these experiments the magnetic field was aligned in-plane along the wire axis. Since the central wire section, detached by nanoconstrictions, was narrower than the (Ga,Mn)As input wires, the coercive fields were different and an antiparallel alignment of the magnetization in the island and the input lines was obtained in a certain magnetic field window. This together with a depletion of charge carriers in the constrictions, hence forming an electrostatic barrier, are the essential ingredients for observing a TMR effect. In subsequent angle dependent measurements for a similar geometry with equally wide wires, where the in-plane magnetic field direction was varied, an enhanced anisotropic magnetoresistance (AMR) was observed [2]. Since the nanoconstrictions in this experiments were also in the tunnelling regime and since the angular dependence was AMR-like, the effect was ascribed to the tunnelling anisotropic magnetoresistance effect (TAMR). The latter was observed before in Au/AlO$_x$/(Ga,Mn)As [3] and (Ga,Mn)As/GaAs/(Ga,Mn)As stacks [4]. In the experiments presented below we explore above effects in 50 nm thick (Ga,Mn)As layers and find an antiferromagnetic arrangement of the central (Ga,Mn)As island to the leads at zero magnetic field as well as an enhanced AMR in a pre-tunnelling regime.

We fabricated (Ga,Mn)As nanostructures consisting of a central island of 100 nm width and 700 nm length that is separated by nanoscale constrictions (≈ 25 nm) from 400 nm wide and 10 μm long (Ga,Mn)As wires (Fig. 1). Additional current and voltage leads connected to the 400 nm wide wire allow four-probe transport measurements. The long axis of the structure is oriented along the [100] (or equivalent) direction which is near the easy axis of the (Ga,Mn)As material. For our samples we used a 50 nm thick Ga$_{1-x}$Mn$_x$As film ($x \approx 2\%$) grown by low temperature molecular beam epitaxy on a semi-insulating GaAs(100) substrate with a 150 nm thick (Al,Ga)As buffer layer [5]. The inset of Fig. 1 shows the temperature dependence of the longitudinal resistance R_{xx}, used to estimate the Curie temperature T_C. From the resistance maximum we extract $T_C \approx 60$ K. The sheet resistance $R_\square$ is 1.8 kΩ at 1 K. From the high field Hall resistance R_{xy} at 90 mK we obtained a hole carrier concentration $p \approx 1.8 \times 10^{20}$ cm^{-3} [6]. Within a 6 band $k \cdot p$ model this corresponds to a Fermi energy of 130 meV [7].

---

[*] Corresponding author: e-mail: markus.schlapps@physik.uni-regensburg.de

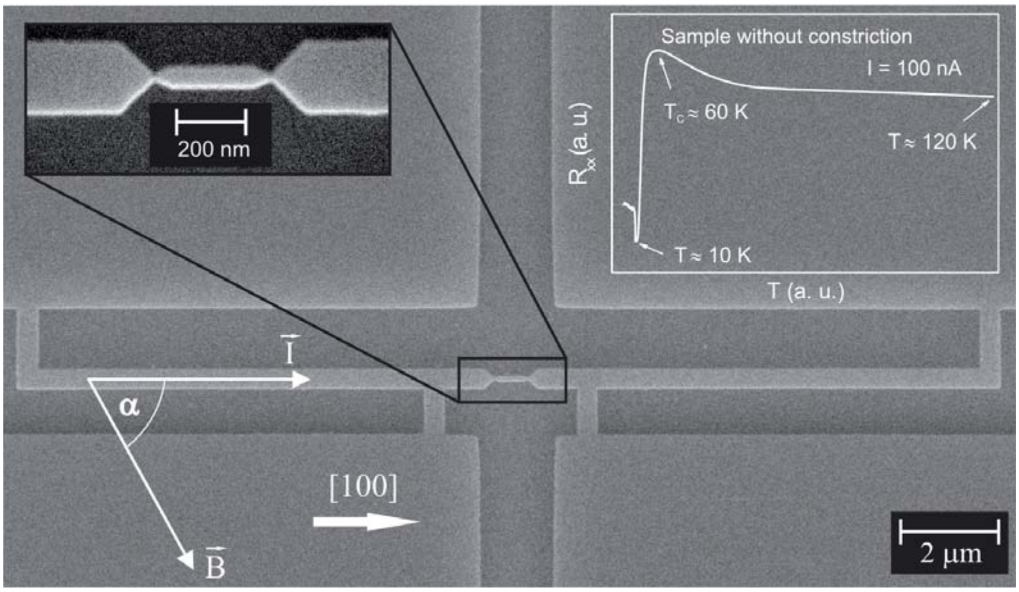

Fig. 1 Scanning electron micrograph (SEM) of a sample with an island, separated by nanoconstrictions from the input leads. The current and voltage leads for four probe measurements are also shown. Current ***I*** is applied along the [100] direction, close to the easy axis, where α is the angle between current ***I*** and the in-plane magnetic field ***B***. The left inset displays a magnification of the central island. The inset on the right hand side shows the temperature dependence of the longitudinal resistance for the (Ga,Mn)As material used to determine T_C in our experiments.

For transport experiments (Ga,Mn)As layers were first pre-patterned with a Hall-bar structure using standard optical lithography and chemical dry etching. After brief ion beam etching (Ar-sputtering) of the surface to remove the native oxide layer, gold contacts were deposited by a standard lift-off method. To define the nanostructures we used electron beam lithography with PMMA as negative resist followed by $SiCl_4$ based reactive ion etching. Magnetotransport measurements are carried out in a ^{4}He bath cryostat with a superconducting magnet and by employing standard lock-in techniques. The direction of the applied external magnetic field relative to the current direction (angle α, see Fig. 1) was varied in-plane by using a rotatable sample holder.

Figure 2a shows an electron micrograph of a ~25 nm wide constriction which turned out to be in the tunnelling regime. A huge TMR effect of ~5000%, similar to the one described in Ref. [1], can be observed at 1.4 K. A corresponding experimental result is displayed in Fig. 2b. The external magnetic field is always applied along the current direction, approximately equal to the easy axis. At high negative fields, e.g., the magnetization of all three parts of the structure is aligned along the field-direction. When the field is increased, a distinct resistance jump occurs at about 4 mT caused by switching of the wires' magnetization. Now island and wire magnetizations are in the antiparallel state. This antiparallel alignment of the magnetization at each constriction is the reason for the resistance increase. The resistance decreases again due to parallel alignment of the magnetizations at higher fields. The three different magnetization configurations are schematically displayed in the insets of Fig. 2b. An interesting feature is observed at higher temperatures (Fig. 2c, d): coming e.g. from positive magnetic fields the switching into the high resistance state occurs at positive magnetic field values. This suggests an antiferromagnetic arrangement between island and wires before the *B*-direction has been reversed. This could reflect the formation of end domains in the vicinity of the junction due to demagnetizing fields. A potential domain configuration is shown in the inset of Fig. 2d. One would expect however two steps in the resistance

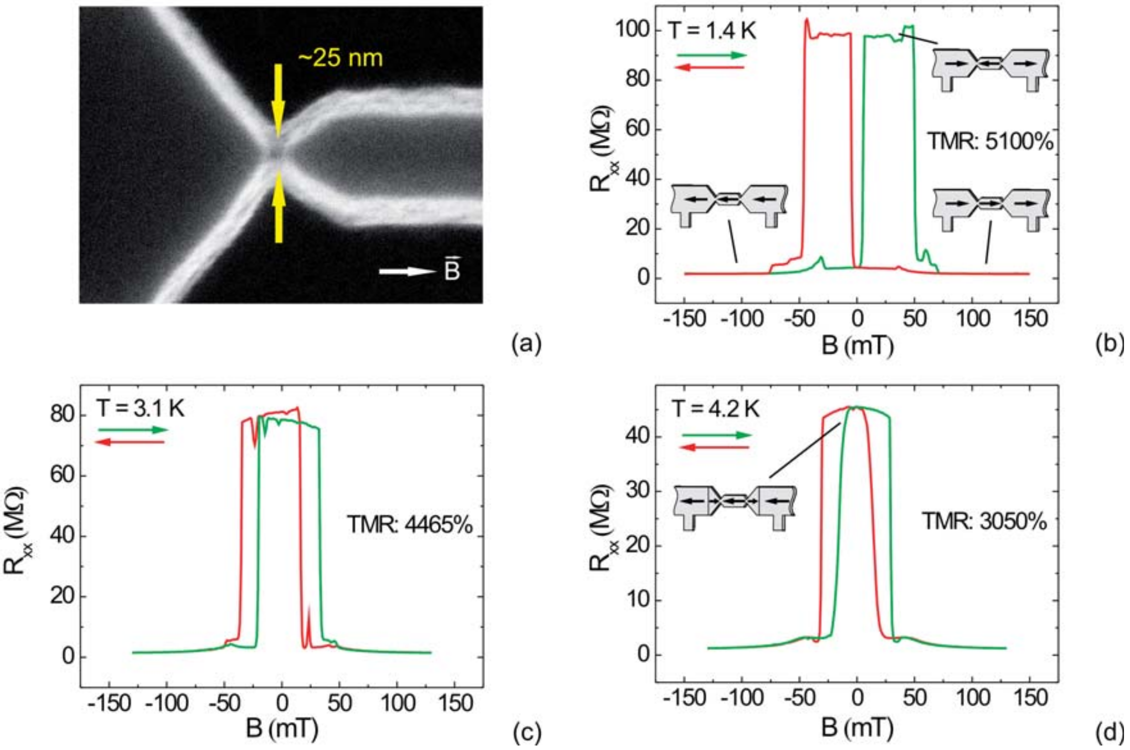

Fig. 2 (online colour at: www.pss-a.com) (a) SEM picture of a 25 nm wide constriction giving rise to a very high TMR effect, shown in (b) for $T = 1.4$ K. The external magnetic field is applied along the [100] direction. The resistance jumps can be attributed to the change in the magnetization configuration of the three domain areas (see insets). The high resistance state corresponds to an antiparallel alignment of island and wire magnetization; (c) TMR of the same sample at 3.1 K and (d) at 4.2 K. The inset sketches a possible domain configuration consistent with a switching event before the magnetic field direction gets reversed. For all shown measurements the applied current was 900 pA in the low resistance state.

before the maximum value is reached unless the formation of both end domains occurs at the same field. More experiments are needed to clarify this point.

Samples with very similar geometry but with a constriction width of ~30 nm do not show such large magnetoresistance effects. A corresponding example is displayed in the right hand column of Fig. 3. In these experiments the direction of the in-plane magnetic field was varied. The data in the right row are compared to corresponding measurements carried out on wires without constrictions (left row). The pronounced magnetoresistance observed in the reference sample can be ascribed to the AMR effect. The jumps reflect switching of the magnetization into an easy direction. The underlying physics was discussed in detail in Ref. [8] and similar magnetoresistance traces were quantitatively modelled within a single domain picture recently [9]. The magnetoresistance size $\Delta R/R$ is angle dependent and ranges between 1% and 4%. Very similar features can be found in the magnetoresistance across the island structure. In addition to the resistance jumps stemming from magnetization switching of the input leads, additional small features emerge from magnetization switching inside the island. The resistance trace of the bottom figure ($\alpha \approx 90°$) is shown on an extended magnetic field scale in Fig. 4 together with a schematics of the magnetization configuration in the different sections of the wire. Remarkably, the overall magnetoresistance increases by a factor 3–5 compared to the unpatterned reference. An enhancement of the AMR effect was recently observed in a system with nanoconstrictions in the tunnelling regime and

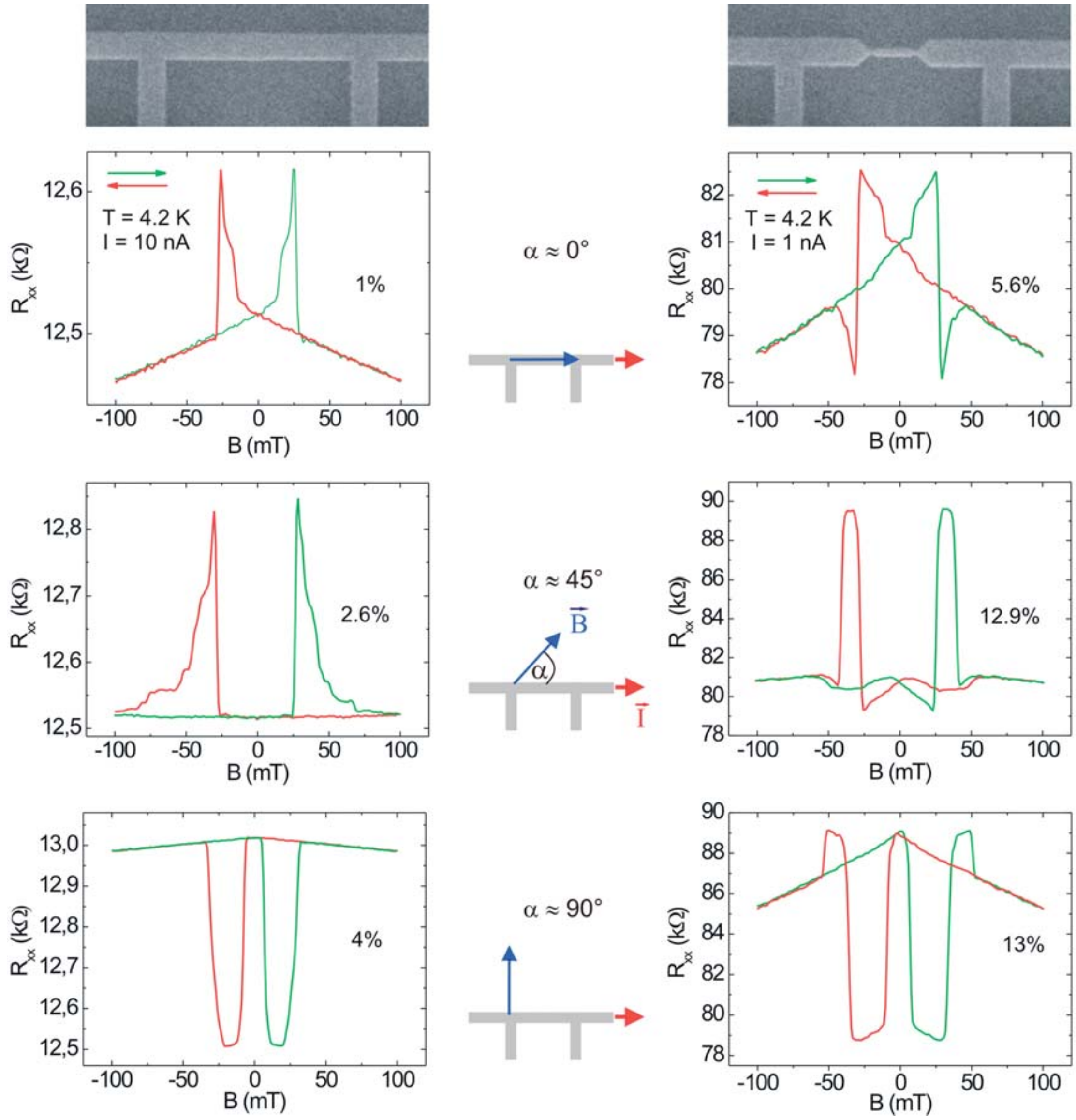

Fig. 3 (online colour at: www.pss-a.com) Comparison of the magnetoresistance for wires without (left) and with (right) nanoisland for three different angles between magnetic field ***B*** and current direction ***I***. Magnetic field and easy direction are slightly misaligned for the 0° trace. Corresponding electron micrographs of the samples' central region are displayed on top. The magnetoresistance features, ascribed to AMR are enhanced for transport across the island. The higher current of 10 nA for the wire without nanoisland was chosen to reduce noise, the size of the effects did not change for 1 nA.

ascribed to the TAMR effect [2]. In our experiment the increase of the resistance from about 12.5 kΩ to 80 kΩ after insertion of nanoconstrictions is expected from the modified geometry alone and tunnelling seems not to be a dominant transport mechanism here. The enhanced magnetoresistance $\Delta R/R$ might result from a reduced carrier density in the vicinity of the constrictions which brings the system closer to the metal-insulator transition. Such an enhanced AMR effect was observed for example for a reduced Mn concentration (and hence reduced carrier density) in unpatterned (Ga,Mn)As films [10].

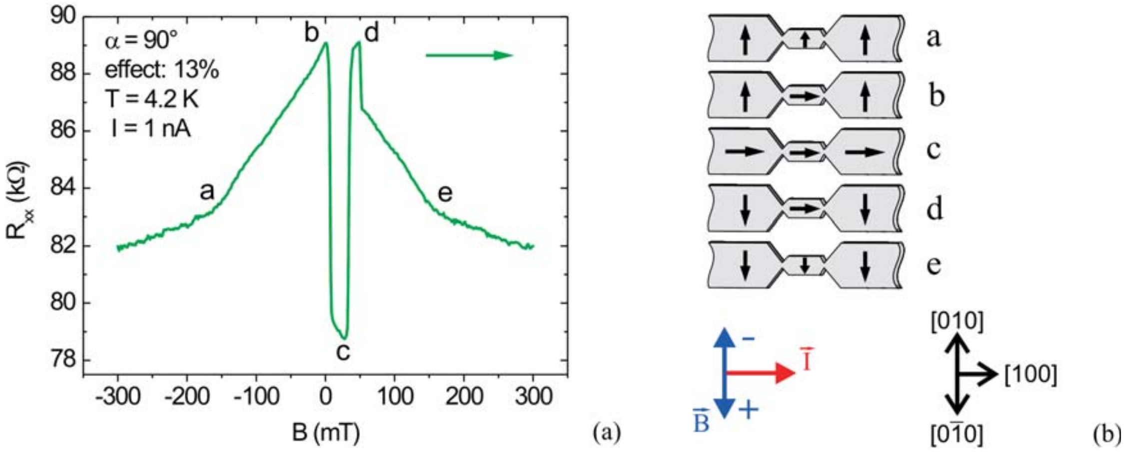

Fig. 4 (online colour at: www.pss-a.com) (a) Magnetoresistance of the right bottom panel of Fig. 3 displayed on an extended magnetic field scale. A sketch of the corresponding magnetization configurations at different magnetic field values is shown in (b). In the experiment the current was flowing along the [100] direction while the magnetic field was aligned perpendicular to the current.

Acknowledgements We thank Rashid Gareev and Günther Bayreuther for valuable discussions and acknowledge support from the Deutsche Forschungsgemeinschaft (DFG) via SFB 689.

References

[1] C. Rüster et al., Phys. Rev. Lett. **91**, 216602 (2003).
[2] A. D. Giddings et al., Phys. Rev. Lett. **94**, 127202 (2005).
[3] C. Gould et al., Phys. Rev. Lett. **93**, 117203 (2004).
[4] C. Rüster et al., Phys. Rev. Lett. **94**, 027203 (2005).
[5] M. Reinwald et al., J. Cryst. Growth **278**, 690 (2005).
[6] K. Wagner et al., cond-mat/0603418 v1 (2006).
[7] T. Dietl et al., Phys. Rev. B **63**, 195205 (2001).
[8] H. X. Tang et al., Phys. Rev. Lett. **90**, 107201 (2003).
[9] S. T. B. Goennenwein et al., Phys. Rev. B **71**, 193306 (2005).
[10] K. Y. Wang et al., Phys. Rev. B **72**, 085201 (2005).