Spin-valve effects involving magnetic semiconductors are of considerable importance for applications in spintronics. Because the carriers in these materials are holes (with strong spin-orbit coupling), it has been difficult to observe spin dependent scattering in the diffusive regime (GMR, or giant magnetoresistance). Tunnel magnetoresistance (TMR) experiments have been more successful, yielding spin-valve effects of several tens of percent.

We have fabricated transport structures consisting of a central island of 100 nm width and 500 nm length connected to two 400 nm wide and 10 μm long wires by constrictions with widths down to 10 nm or less. The constrictions act as pinning centers for DW. The 400 nm wide wires are contacted by voltage- and current-leads, allowing four-probe transport measurements. The contact pads were defined on the (Ga,Mn)As layer by e-beam lithography, evaporation of W and Au, and lift-off. Subsequently, the wires and constrictions were defined by negative e-beam lithography. Cl₂-based dry-etching was used to etch through the (Ga,Mn)As, leaving (Ga,Mn)As underneath the resist and metallization. The long axis of the island is oriented along the [100]- (or equivalent) direction of the (Ga,Mn)As, which is near the magnetic easy axis of this layer, as determined by SQUID and consistent with Ref. 9. By leaving the resist on the sample we can further etch it and narrow the constrictions.

We study symmetric double constriction samples in order to avoid complications associated with thermoelectric voltages. Moreover, the sample layout is such that the shape anisotropy causes the (magnetically isolated) inner island to switch at different fields than the outer wires. We verified by SQUID magnetometry that while the wide leads switch magnetization at around 15-20 mT (depending on lithographic parameters), the island exhibits switching fields of order 60-90 mT. The coercive field of the unpatterned epilayer is ≈ 8 mT.

MR measurements are carried out at 4.2 K in a He bath cryostat with a superconducting magnet. The magnetic field is applied parallel to the current direction. Four-probe DC measurements of the magnetoresistance are performed at constant voltage using zero-offset voltage- and current-preamplifiers. During the measurement the magnetic field is varied from full negative saturation of the material to full positive saturation and back.

The inset in Fig. 1 schematically describes the experimentally observed behavior of the MR as a function of magnetic field. The inset includes a typical MR curve with a negative coercive field at full negative saturation and a positive coercive field at full positive saturation. The MR curve shows a sharp drop at the negative coercive field and a gradual increase at the positive coercive field. The inset also includes a schematic of the sample layout, with the magnetic field applied perpendicular to the plane of the sample. The inset is labeled with the sample dimensions and the orientation of the magnetic field relative to the sample axes.
FIG. 1: False-color SEM picture (side-view) of a double constriction showing part of the outer wires with the voltage leads. Note the resist that is still present on the wire. The insets show the relative magnetization of the parts (left) and the resulting schematic MR trace for sweep-up (solid line) and sweep-down (dashed line).

Expected MR of our device. Sweeping the field from large negative to positive values causes the outer wires to switch first, inducing antiparallel alignment of the island and the wires. In this state, DW are present at the constrictions and the resistance is increased. At larger positive fields the magnetization of the island is also reversed, leaving all areas aligned in parallel and the resistance returns to its original value. The magnetization reversal is hysteretic, leading to the depicted spin-valve-like MR.

Experimentally, all samples exhibit the expected MR. The amplitude of the effect depends strongly on the resistance of the constrictions. Fig. 2(a) shows the MR of a representative sample with a four-terminal resistance of \( \approx 48 \, k\Omega \). The MR is spin-valve-like with the correct hysteresis, and the critical fields agree with the SQUID results. We regard this as evidence that our design successfully incorporates both shape-anisotropy-controlled switching and strong pinning of DW in the constrictions.

For comparison, the inset of Fig. 2(a) shows the MR of a 400 nm wire without constrictions which shows only 0.3% bulk-like anisotropic MR, with switching at \( \approx 20 \, mT \). In Fig. 2(a), the maximum MR is \( \approx 1.5\% \).

Because the resist remains on the sample after fabrication, we can apply a further dry etching step producing a sample with narrower constrictions, but with approximately the same width of island and leads. Applying this procedure to the sample of Fig. 2(a), the additional etching brought the device resistance up to \( \approx 78 \, k\Omega \) while the MR effect increased to about 8% (Fig. 2(b)).

The fine structure on the peaks of the as-fabricated sample was completely reproducible, whereas for the re-etched sample it varied from sweep to sweep as evident in the figure. This could suggest the presence of multiple pinning sites near the constrictions. The different pinning sites would yield different geometrical confinement of the DW, thus altering their resistance. Because of the extremely small dimensions realized here, impurities and side wall roughness by etching are likely causes.

A very strong increase in MR is obtained when the constrictions are etched still further. In Fig. 3 we plot the MR of a sample with a zero field resistance of 4 M\( \Omega \) and a positive MR of nearly 2000\%. From the bulk resistivity of the material, we estimate that the leads and wires in our devices contribute only \( \approx 40 \, k\Omega \) to the resistance, implying that the constrictions now act as tunnel barriers. In addition, the I-V characteristics of the sample are strongly non-linear with a quadratic dependence of the conductance on bias that is characteristic of tunneling transport[11]. This suggests that the observed very large MR could be due to TMR. We also note that, in contrast with the results in Fig. 2, we now observe a hysteretic signal around zero field (although a major jump in resistance still occurs at the 20 mT expected from the wide leads). This observation is also consistent with the presence of tunnel barriers, in that these cause a magnetic decoupling of the island and the wires. We suggest that in Fig. 3 the magnetization of the island no longer switches by the introduction of a DW through a constriction but rather by magnetic rotation, which explains the MR at zero field: If the structure is not perfectly aligned along the easy axis, the relatively wide wires will be magnetized slightly off-axis at zero field while the narrow island is fully dominated by shape anisotropy, so that
the relative alignment is not fully parallel. In wider constrictions the magnetic coupling prevents this effect and MR is observed only at finite fields.

We can understand the above observations in a unified manner by assuming that etching causes a gradual depletion of the carrier density at the constrictions. Dry etching of semiconductors damages the walls of the epilayer, and the resulting charged impurities induce sidewall depletion of the interior of the semiconductor, a mechanism that clearly will be most effective at the narrowest parts of the structure, i.e. at the constrictions. In the numerical estimates below, we assume both constrictions have equal resistance. Note that deviations from this assumption have only minor effects on the drawn conclusions.

As a first order approximation, we assume that the DWR is given by the expression of Valet and Fert\[12\] for the spin-accumulation-induced resistance at an abrupt junction between two regions of opposite magnetization:

$$\Delta R \approx 2\beta^2 \rho^* \ell,$$

where $\rho^*$ is the spin-symmetric bulk resistivity in the magnetic material, $\ell$ is the length of the constriction and $\beta$ is the spin polarization in the constriction given by

$$\beta = \frac{N_\uparrow(E_F)v_{F\uparrow} - N_\downarrow(E_F)v_{F\downarrow}}{N_\uparrow(E_F)v_{F\uparrow} + N_\downarrow(E_F)v_{F\downarrow}} = \frac{E_{F\uparrow} - E_{F\downarrow}}{E_{F\uparrow} + E_{F\downarrow}}.$$  \hspace{1cm} (2)

Here we have used that in a parabolic band model both the densities of states at the Fermi energy $N_{\uparrow,\downarrow}(E_F)$ and the Fermi velocities\[13\] $v_{F\uparrow,\downarrow}$ are proportional to $k_F$ (the arrows refer to the spin subbands). From Eq. 2 one can see the evolution of the resistance and MR with etching. We assume that etching depletes the (Ga,Mn)As, so that $E_{F\uparrow}$ and $E_{F\downarrow}$ are reduced, but the exchange splitting $\Delta E = E_{F\uparrow} - E_{F\downarrow}$ remains roughly the same. Hence the numerator of Eq. 2 does not change, but the denominator gets smaller and the polarization increases.

We now insert this expression for the polarization into the Valet-Fert expression (Eq. 1) for the MR. Calculating the resistance $R_c$ of the constrictions by subtracting $\approx 40 \text{k}\Omega$ from the device resistance, and taking a reasonable value of $\Delta E \approx 30 \text{ meV}$ for the exchange splitting, we reproduce the observed MR in Fig. 2a using the Fermi energy of 150 meV found for the unetched sample, while the data in Fig. 2b imply a reduction of the Fermi energy to about 90 meV. These values seem quite reasonable, but should, given the many uncertainties and approximations involved, only serve as a rough indication of what may be going on in the sample. Note that the spin polarization of some 20% obtained from these numbers is only a lower limit estimate of the bulk value: we know that the transport mean free path $\ell_t$ of the holes is shorter than the dimensions of the constriction, so we can assume that substantial spin relaxation is taking place.

We now turn to the data in Fig. 3b, where the constrictions clearly are in the tunneling regime. It is tempting to try to model the observed MR in terms of Julliere’s TMR model\[15\]. In order to explain a 2000 % MR signal, the Julliere model requires a spin polarization of the contacts of ca. 95 %, much larger than the values found above. This large discrepancy suggests that the model in Ref. \[15\] is not applicable here and we have therefore adopted a different approach to modelling the tunneling regime. We also note that a model of the MR effect due to the joint effects of both constrictions \[16\] can be ruled out because of the long distances between the barriers and the very short mean free path. We can therefore safely consider a model based on two independent barriers.

We assume that the etching process creates a shallow barrier of parabolic shape between the two regions of (Ga,Mn)As, as shown in Fig. 3a. We define the barrier height for the majority-spin holes above the chemical potential $\mu$ as $E_B$. If the barrier is very thin, such that the hole wave functions can penetrate into the barrier region and continue to couple the Mn spins, then it is reasonable to assume that $\Delta E$ in the barrier region is the same as in the bulk. This results in a barrier for minority-spin holes that is higher ($E_B + \Delta E$) than for majority-spin holes ($E_B$). As a consequence of the non-abrupt barrier, the thickness of the barrier for minority-spin holes, $L_{P\downarrow}$, will be greater than that for majority spin holes, $L_{P\uparrow}$.

In the antiparallel situation depicted on the right, however, the barriers for the two spin channels are the same at approximately $E_B + \Delta E/2$, and their thicknesses are also the same, $L_A \approx (L_{P\uparrow} + L_{P\downarrow})/2$. The transmission
probability $T$ through a parabolic barrier is[17]

$$T = \exp \left( -\frac{\pi m^* (1/2) E_H^{(1/2)} L}{2^{3/2} \hbar} \right)$$

(3)

where $E_H$ and $L$ are the height and thickness of the barriers respectively, and $\hbar$ is the reduced Planck constant. With $m^* \approx 0.5m_o$, we have $T = \exp \left(-3.0E_H^{(1/2)} L\right)$, where $E_H$ is in eV and $L$ in nm.

We now estimate the values of the parameters required to match the experiment. Assuming that the parabolic shape of the barrier is the same for all situations, there is a uniform relationship between $L$ and $E_H$ of the form $L = (\alpha E_H)^{(1/2)}$, where $\alpha$ is constant. This implies that $T = \exp \left(-3.0\alpha^{(1/2)} E_H\right)$. From the experiment we have $T_{\parallel}/T_{\perp} = 20$, and so we choose $\alpha$ to satisfy this. With $\Delta E \approx 30$ meV, this yields $\alpha = 4400$ eV$^{-2}$, independently of the barrier height for majority spin holes $E_B$. We can estimate $E_B \approx 31$ meV from the resistance of the constrictions. Just as a gauge, the thicknesses of the barriers are then 11.7 nm for the parallel majority case, 14.3 nm for the antiparallel case, and 16.4 nm for the parallel minority case. These numbers all seem reasonable.

A key element of this analysis is that the minority and majority carriers deplete at different positions in the constriction. Depletion at the edge of a (Ga,Mn)As film differs considerably from depletion in the bulk, since Mn spins at the edge remain coupled through the remaining holes to Mn spins which lie effectively within the bulk. The presence of these nearby bulk-like oriented Mn spins produces, through the mediating holes, a large exchange field on the Mn spins at the edge. This in turn induces them to order at local hole concentrations which, in the bulk, would otherwise not lead to ferromagnetism. Hence we argue that magnetically ordered Mn spins, producing an exchange splitting for the holes similar to that in bulk, are present at the edges of the sample where the local hole concentrations is much lower than the bulk.

Finally, we turn to the observation of a voltage dependence shown in the inset of Fig. 2b. The relative amplitude of the MR peak decreases exponentially with increasing bias voltage $V_{bias}$. A qualitatively similar behavior is observed for all samples with constrictions that are not in the tunneling regime. A bias dependence of the current across a ferromagnetic DW was discussed theoretically in Refs. [3], but not observed previously. By analogy to a semiconducting p-n junction, an exponential increase ($\propto \sinh(eV_{bias}/kT)$) of the (electrical) current through the DW is expected. This should lead to an exponential suppression of the MR signal as observed in the inset of Fig. 2. However, instead of the expected slope of $e/kT$, we find an activation energy of around 11 meV, or 35 K. Part of the discrepancy stems from the fact that not all the applied bias drops across the constrictions (a factor of 2 in this case), and another factor of 2 comes from the fact that our devices have two constrictions. Nonetheless, the deviation from Refs. [3] is so large that we assume additional physics is at work here. We suggest that the discrepancy may be caused by high electric fields at the constrictions at elevated bias. In semiconductors, such fields may cause drift effects to dominate the transport[15], causing a strong reduction of the up-stream spin diffusion length. This would substantially modify the exponential increase of the current. It would be of interest to investigate such effects in detail, both experimentally and theoretically.

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