

Very Large Magnetoresistance in Lateral Ferromagnetic (Ga,Mn)As Wires with Nanoconstrictions

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We have fabricated (Ga,Mn)As nanostructures in which domain walls can be pinned by sub-10 nm constrictions. Controlled by shape anisotropy, we can switch the regions on either side of the constriction to either parallel or antiparallel magnetization. All samples exhibit a positive magnetoresistance, consistent with domain-wall trapping. For metallic samples, we find a magnetoresistance up to 8%, which can be understood from spin accumulation. In samples where, due to depletion at the constriction, a tunnel barrier is formed, we observe a magnetoresistance of up to 2000%.

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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) [1]. Tunnel magnetoresistance (TMR) experiments have been more successful, yielding spin-valve effects of several tens of percent [2].

It was recently pointed out [3] that large MR effects can be expected from domain walls (DW) in magnetic semiconductors due to the large spin polarization in these materials. Domain-wall resistance (DWR) in ferromagnetic metals, where small effects are typical, has been intensively investigated [4]. Large MRs, however, have been observed in mechanically manipulated nanojunctions [5], though magnetostriction can play a role [6].

Here we address the suggestion of Ref. [3] in an experimental study of DWR in the ferromagnetic semiconductor (Ga,Mn)As. We use lateral nanofabricated constrictions in single domain wires to pin the DW and reduce their length [7]. This approach facilitates ballistic hole transport through the DW, while the lateral fabrication technology excludes any influence of magnetostriction effects [6]. We find that DWR leads to very large spin-valve effects in both the GMR (up to 8%) and TMR (2000%) regimes.

Our samples were made from a thin (19 nm) epitaxial layer of $\text{Ga}_{0.976}\text{Mn}_{0.024}\text{As}$, grown on a semi-insulating GaAs (001) substrate by low temperature molecular beam epitaxy. The carrier density from etch capacitance-voltage calibrations is about $3 \times 10^{20} \text{ cm}^{-3}$, and the sheet resistivity at 4.2 K is about $4.5 \text{ k}\Omega/\square$. Assuming an effective hole mass as in GaAs, $m^* \approx 0.5m_e$, where m_e is the free electron mass, these values imply a Fermi energy E_F of 150 meV, a Fermi wavelength

λ_F of 6 nm, and a transport mean-free path l_t of ca. 1 nm. The Curie temperature is 65 K.

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 $10 \mu\text{m}$ long wires by constrictions with widths down to 10 nm or less (Fig. 1). 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. Cl_2 -based dry etching was used to etch through the (Ga,Mn)As, leaving

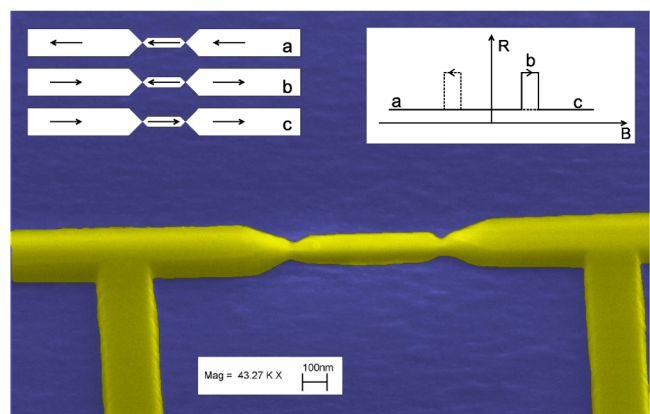


FIG. 1 (color online). False-color SEM picture (side view) of a double constriction showing part of the outer wires with the voltage leads. Note the resist that is still present on the wire. The insets show the relative magnetization of the parts (left) and the resulting schematic MR trace for sweep-up (solid line) and sweep-down (dashed line).

(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 [9]. 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 the order of 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 of Fig. 1 schematically describes the 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 hysteric, 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. Figure 2(a) shows the MR of a representative sample with a four-terminal resistance of ≈ 48 k Ω . 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% bulklike anisotropic MR, with switching at ≈ 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 ≈ 78 k Ω while the MR effect increased to about 8% [Fig. 2(b)].

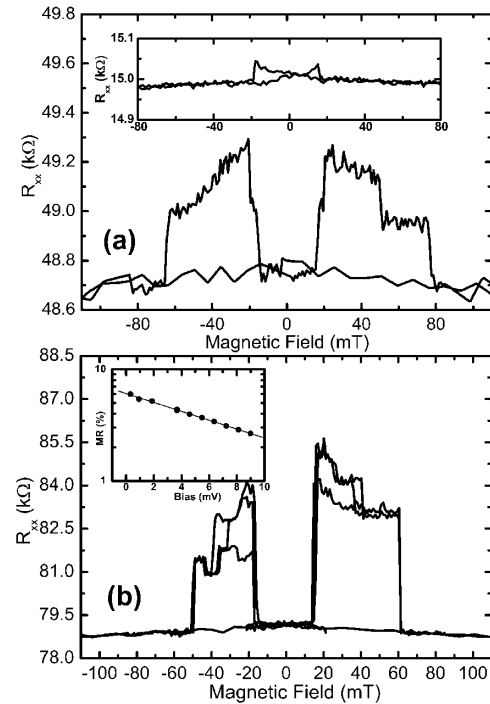


FIG. 2. MR of a representative sample as fabricated (a) and after further etching (b). The inset in (a) shows the MR of a wire without constrictions, whereas the inset in (b) shows that the MR is reduced exponentially with bias voltage.

The fine structure on the peaks of the as-fabricated sample was completely reproducible, whereas for the reetched sample it varied from sweep to sweep as is 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 caused 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 Ω 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 ≈ 40 k Ω to the resistance, implying that the constrictions now act as tunnel barriers. In addition, the I - V characteristics of the sample are strongly nonlinear with a quadratic dependence of the conductance on bias that is characteristic of tunneling transport [10]. 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 hysteric 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

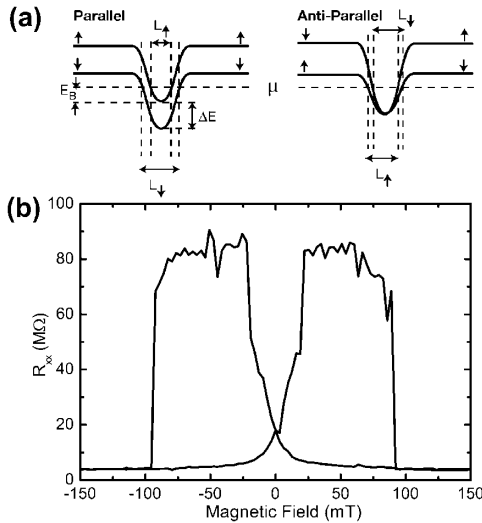


FIG. 3. (b) MR in a sample with tunnel barriers at the constrictions. The top panel (a) depicts schematically the tunneling events taking place in the sample.

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 [11] for the spin-accumulation-induced resistance at an abrupt junction between two regions of opposite magnetization:

$$\Delta R \approx 2\beta^2 \rho^* \ell, \quad (1)$$

where ρ^* is the spin-symmetric bulk resistivity in the magnetic material, ℓ is the length of the constriction, and β is the spin polarization in the constriction given by

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

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 [12] $v_{F\uparrow,\downarrow}$ 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 ≈ 40 k Ω from the device resistance, and taking a reasonable value [13] of $\Delta E \approx 30$ meV for the exchange splitting, we reproduce the observed MR in Fig. 2(a) using the Fermi energy of 150 meV found for the unetched sample, while the data in Fig. 2(b) 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, serve only 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 l_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 of Fig. 3(b), 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 [14]. 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 modeling the tunneling regime.

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. 3(a). We define the barrier height for the majority-spin holes above the chemical potential μ 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 ΔE 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 nonabrupt 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 \mathcal{T} through a parabolic barrier is [15]

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

where E_H and L are the height and thickness of the barriers, respectively, and \hbar is the reduced Planck constant. With $m^* \approx 0.5m_e$, we have $\mathcal{T} = \exp[-3.0E_H^{(1/2)}L]$, 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 α is constant. This implies that $\mathcal{T} = \exp[-3.0\alpha^{(1/2)}E_H]$. From the experiment we have $\mathcal{T}_{P\uparrow}/\mathcal{T}_A = 20$, and so we choose α to satisfy this. With $\Delta E = 30$ 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 bulklike 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 are much lower than the bulk.

Finally, we turn to the observation of a voltage dependence shown in the inset of Fig. 2(b). 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 Ref. [3], but not observed previously. By analogy to a semiconducting p - n junction, an exponential increase [$\propto \sinh(eV_{\text{bias}}/kT)$] 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 $35kT$. 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 Ref. [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 [16], 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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