The onsets of the transitions are all in the vicinity of 36 K, the transition temperature for $x = 0.10$. There is no bulk superconducting transition for $x = 0.3$ and $x = 0.4$. The data are interpreted as indicating that bulk superconductivity in single-phase material is suppressed for $x$ greater than 0.10. The superconducting transitions observed in the two-phase region are due to both the decreasing amount of the bulk superconducting phase with increasing Al content, and also to the distribution of Al contents in the powders. The structural and magnetic data taken together therefore indicate that the disappearance of bulk superconductivity in $Mg_{1-x}AlB_2$ occurs at the same Al concentrations at which a structural transition occurs—this transition results in the partial collapse of the separation between boron planes.

The similarity of the calculated electronic density of states (DOS) for MgB$_2$ and AlB$_2$ (ref. 6) indicates that the effect of substituting Al for Mg can be considered as a simply filling of available electronic states, with one electron donated per Al, within a ‘rigid band’ picture. The calculations show that there is a sharp drop in the DOS of MgB$_2$ at only slightly higher electron concentrations. The gradual decrease of $T_c$ from 38 to 36 K with increasing Al content in the single-phase region below $x = 0.1$ may therefore be due to the expected decrease of the DOS at $E_F$ with increasing electron count, consistent with a conventional origin for the superconductivity.

High-resolution structural study of uniform powders, if they prove possible to synthesize, would help to determine how the superconductivity and the structural transition are linked on an electronic level. The proximity of MgB$_2$ to a structural instability is consistent with a general picture for conventional high-temperature superconductors as being near chemical phase instability owing to strong electron–lattice coupling. However, our data for $Mg_{1-x}AlB_2$ do not suggest that the structural instability in this case is driven by competition between superconductivity and a structural distortion that would decrease the density of electronic states at the Fermi energy; this is because the Al substitution both decreases $T_c$ and decreases the DOS at $E_F$ before the transition occurs. It is at first sight surprising that the observed structural instability in MgB$_2$ involves a partial collapse of the separation of the boron layers, not a change in the boron–boron in-plane distance. It will be of interest to determine whether this collapse is associated with special characteristics of the electronic band filling near 0.1 excess electrons per cell.

Acknowledgements

This work was supported by the US Department of Energy and the National Science Foundation.

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Electrical spin injection and accumulation at room temperature in an all-metal mesoscopic spin valve

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Finding a means to generate, control and use spin-polarized currents represents an important challenge for spin-based electronics$^{1–3}$, or ‘spintronics’. Spin currents and the associated phenomenon of spin accumulation can be realized by driving a current from a ferromagnetic electrode into a non-magnetic metal or semiconductor. This was first demonstrated over 15 years ago in a spin injection experiment$^4$ on a single crystal aluminium bar at temperatures below 77 K. Recent experiments$^5–^8$ have demonstrated successful optical detection of spin injection in semiconductors, using either optical injection by circularly polarized light or electrical injection from a magnetic semiconductor. However, it has not been possible to achieve fully electrical spin injection and detection at room temperature. Here we report room-temperature electrical injection and detection of spin currents and observe spin accumulation in an all-metal lateral mesoscopic spin valve, where ferromagnetic electrodes are used to drive a spin-polarized current into crossed copper strips. We anticipate that larger signals should be obtainable by optimizing the choice of materials and device geometry.

Spin accumulation plays an important role in spin-polarized...
Transport phenomena such as giant magnetoresistance (GMR), domain-wall magnetoresistance and spin-current-induced magnetization switching experiments\textsuperscript{3–12}. We wanted to study the effect isolated from other spin-related phenomena, such as spin-dependent interface scattering, anisotropic magnetoresistance (AMR) and Hall effects. Large spin-accumulation effects have been claimed, using a ferromagnet–normal-metal–ferromagnet sandwich geometry\textsuperscript{13,14}. However, the interpretation of the data has raised problems, because the magnitude of the observed effect requires a spin polarization of the current in the normal metal of around 100% (refs 15–18). Another problem is that the magnetoresistance effects of the ferromagnetic contacts, such as AMR and Hall effects, can mask or even mimic the spin-accumulation signal.

We have fabricated mesoscopic lateral spin valves to isolate the spin accumulation signal completely, using a multi-terminal geometry. In our spin-injection experiments, we use permalloy Ni\textsubscript{80}Fe\textsubscript{20} (Py) electrodes to drive a spin-polarized current into copper (Cu) cross strips (Fig. 1). We observe clear spin valve junctions at copper (Cu) cross strips (Fig. 1). We observe clear spin valve signals at $T = 4.2$ K, as well as at room temperature. From our analysis we deduce a spin-flip length $\lambda_s$ in the Cu wire of about 1 $\mu$m at 4.2 K, which is reduced to about 350 nm at room temperature.

Two batches of samples were made in a two-step lift-off process, using electron-beam lithography for patterning. The first batch (1) had a fixed Py electrode spacing $L$ of 250 nm, and in the second batch (2) $L$ is varied from 250 nm to 2 $\mu$m. To avoid magnetic fringe fields from the ferromagnetic electrodes, the 40-nm-thick Py electrodes (Py1, Py2) were sputter deposited first on a thermally oxidized silicon substrate. Different geometric aspect ratios of Py1 and Py2 are used to obtain different coercive fields\textsuperscript{19}. We can thus control the relative magnetization configuration (parallel/anti-parallel) of Py1 and Py2, by sweeping an applied magnetic field $B$, directed parallel to their magnetic easy axis. The sizes of Py1 and Py2 in batch 1 were $2.0 \times 0.8 \mu$m\textsuperscript{2} and $14 \times 0.5 \mu$m\textsuperscript{2} respectively, as shown in Fig. 1a. An additional set of Py1 and Py2, with sizes of $2.0 \times 0.5 \mu$m\textsuperscript{2} and $14 \times 0.1 \mu$m\textsuperscript{2}, was used in batch II. This set showed an improved magnetic switching behaviour and had coercive fields three times larger.

In the second fabrication step, 50-nm-thick crossed Cu strips were deposited by e-gun evaporation in $1 \times 10^{-3}$ mbar vacuum. Before Cu deposition, the oxide of the Py electrodes was removed by ion milling, to ensure transparent contacts. The conductivities of the Py and Cu films were determined to be $\sigma_{Py} = 6.6 \times 10^{5} \Omega^{-1} \text{m}^{-1}$ and $\sigma_{Cu} = 3.5 \times 10^{7} \Omega^{-1} \text{m}^{-1}$ at room temperature. At 4.2 K both conductivities increased by a factor of 2.

The measurements were performed by standard a.c. lock-in techniques, using current magnitudes of 100 $\mu$A to 1 mA. We note that in the 'conventional' spin-valve geometry (sending a current $I$ from contacts to 1 to 7, and measuring the voltage $V$ between contacts 4 and 9), the signal $R = V/I$ was completely dominated by AMR and Hall effects of the Py contacts, having a typical magnitude of 10 m$\Omega$. Although we have used the AMR signal of the contacts to confirm the switching of the Py electrodes, its presence has made

![Figure 1](image1.png)

**Figure 1** Sample layout. a, Scanning electron microscope image of the mesoscopic spin valve junction. The two wide horizontal strips are the ferromagnetic electrodes Py1 and Py2. The vertical arms of the Cu cross (contacts 3 and 8) lie on top of the Py strips; the horizontal arms of the Cu cross form contacts 5 and 6. Contacts 1, 2, 4, 7 and 9 are attached to Py1 and Py2 to allow four terminal AMR measurements of the Py electrodes. b, Schematic representation of the non-local measurement geometry. Current is entering from contact 1 and extracted at contact 5. The voltage is measured between contacts 6 and 9.

![Figure 2](image2.png)

**Figure 2** The spin valve effect at $T = 4.2$ K (a) and room temperature (b) in the non-local geometry for a sample with 250 nm Py electrode spacing. An increase in resistance is observed, when the magnetization configuration is changed from parallel to anti-parallel. The solid (dashed) lines correspond to the negative (positive) sweep direction. c, d, The ‘memory effect’. For clarity c and d are offset downwards. We note that the vertical scale of a is different from that of b, c and d. The sizes of the Py1 and Py2 electrodes are $2.0 \times 0.5 \mu$m\textsuperscript{2} and $14 \times 0.1 \mu$m\textsuperscript{2}.

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any observation of a spin-valve signal in the conventional spin-valve geometry impossible.

However, in the non-local spin-valve geometry (see Fig. 1b) these spurrious effects can be eliminated. This technique is similar to the “potentiometric” method of Johnson13,14. However, in our case, we have completely separated the current and the voltage circuits. Current now enters from contact 1 (Py1) and is extracted at contact 5 (Cu), whereas the voltage is measured between contact 6 (VCu) and contact 9 (VPy2). Changing the relative magnetization configuration of Py1 and Py2 from parallel to anti-parallel will yield a signal only if the densities (electrochemical potentials) of the spin-up and spin-down electrons in the centre of the Cu cross are unequal. In a parallel configuration Py2 will measure the highest value of the two unequal spin electrochemical potentials, whereas in an anti-parallel configuration it will measure the lower value. Changing from a parallel to an anti-parallel configuration will therefore decrease the voltage (VPy2) measured by Py2, resulting in an increase in the voltage difference (VCu − VPy2) measured, and hence an increase of the resistance.

Figure 2a and b shows typical data taken at 4.2 K and room temperature for a sample from batch II, with a 250-nm Py electrode spacing. While sweeping the magnetic field from negative to positive field, we observed an increase in the resistance when the magnetization of Py1 flips at 9 mT, resulting in an anti-parallel magnetization configuration. When the magnetization of Py2 flips at 47 mT (4.2 K) and 38 mT (room temperature), the magnetizations are parallel again, but now point in the opposite direction. The magnitude of the measured background resistance, around 30 Ω at 4.2 K and 120 Ω at room temperature, depends on the geometrical shape of the Cu cross and is typically a fraction of the Cu square resistance.

Figure 2c and d shows the ‘memory effect’. Coming from high positive B field, the sweep direction of the B field is reversed after Py1 has switched, but Py2 has not. At the moment of reversing the sweep direction, the magnetic configuration of Py1 and Py2 is anti-parallel, and accordingly a higher resistance is measured. When the B field is swept back to its original high positive value, the resistance remains at its increased level until Py1 switches back at a positive field of 9 mT. At zero B field the resistance can therefore have two distinct values, depending on the magnetic history of the Py electrodes. Samples with larger Py electrode spacing show identical switching behaviour, but the magnitude of the spin signal ∆R is reduced, as we will discuss below.

We have calculated the theoretically expected magnitude and the Py electrode distance dependence of the spin valve signal ∆R for the non-local geometry of Fig. 1b in the diffusive transport regime and for transparent interfaces, following the lines of the standard Valet Fert model for GMR20,21, adopted for our multi-terminal geometry. We obtain:

$$\Delta R = \frac{\lambda_N \sigma_a^a}{\sigma_a \sigma_a^d} \left(1 - \frac{L}{2\lambda_N}\right)$$

where \(M = (\lambda_N \sigma_a^a/\lambda_N \sigma_a^d)(1 - \alpha_F)\), \(\alpha_F = \sigma_a - \sigma_d/\sigma_a + \sigma_d\) is the bulk current polarization of the Py electrodes, \(\sigma_a (\sigma_d)\) are spin up (down) conductivities in the ferromagnet, \(\lambda_N (\lambda_F)\) is the spin-flip length in the normal metal (ferromagnetic metal), \(L = l_c / 2\) is the distance between the two Py electrodes, and \(A\) is the cross-sectional area of the normal metal wire. Equation (1) shows that for \(\lambda_N \ll L\), the magnitude of the spin signal \(\Delta R\) will decay exponentially as a function of \(L\). In the opposite limit, \(\lambda_N \gg L\), the spin signal \(\Delta R\) has a 1/L dependence. We note that the spin signal \(\Delta R\) is determined by the bulk conductances of the ferromagnet and normal metal over a distance of the spin-flip lengths. The origin of the spin signal is therefore different from the spin-dependent transport in tunnel junction experiments, where the density of states at the interface is the important quantity for the magnitude of the spin signal23. Hence, for tunnel junctions, the nature of the first atomic layers near the interface is crucial, whereas for transparent contacts, which is the case for our device, the interface properties are expected to be less important15,21.

We have measured the reduction of the magnitude of spin signal \(\Delta R\) as a function of the Py electrode spacing \(L\), as shown in Fig. 3. By fitting the data to equation (1) we have obtained \(\lambda_N\) in the Cu wire. From the best fits we find \(\lambda_N = 1 \pm 0.2 \mu m\) at \(T = 4.2 K\), and \(\lambda_N = 350 \pm 50 \mu m\) at room temperature. The values of \(\lambda_N\) are compatible with those reported in the literature24: \(\lambda_N \approx 450 nm\) for Cu in GMR measurements at 4.2 K. However, we cannot make a straightforward comparison between the GMR results and ours. In the thin films we use, the elastic mean free path of the electrons is limited by surface scattering, causing the conductivity of the Cu to be smaller than in GMR layers. We also note that in Fig. 3 no good fit can be obtained for data where \(L = 250 nm\). As the Py electrode spacing \(L\) approaches the width \(W\) of the Cu wire, the presence of the side arms (Fig. 1a) will give rise to a local enhancement of the conductance at the Cu cross and hence can result in an increase in the spin signal. Therefore, in this limit, we can expect deviations from our one-dimensional model.

We can calculate the spin-flip times \(\tau_{sf}\) in the Cu wire, using a Fermi velocity of \(v_F = 1.57 \times 10^6 m/s\) (ref. 25). At 4.2 K we find \(\tau_{sf} = 42 ps\), while at room temperature \(\tau_{sf} = 11 ps\). We will not discuss the physics of the spin-flip scattering process here. However, comparing the spin-flip time to the elastic scattering time \(\tau_E = 2.9 \times 10^{-14} s\) at 4.2 K, we find that on average the spin is flipped after about 10 elastic scattering events in the Cu wire.

In principle the fits of Fig. 3 also yield the spin polarization \(\alpha_F\) and the spin-flip length \(\lambda_F\) of the Py electrodes. However, the values of \(\alpha_F\) and \(\lambda_F\) cannot be determined separately, because in the relevant limit \((M \gg 1)\) which applies to our experiment \((12 \leq M \leq 26)\), the spin signal \(\Delta R\) is proportional to the product \(\alpha_F^2 \lambda_F^2\). From the fits we find \(\alpha_F \lambda_F = 1.2 nm\) at 4.2 K and \(\alpha_F \lambda_F = 0.5 nm\) at room temperature. Taking, from refs 17 and 18, a spin-flip length in the Py electrode of \(\lambda_F = 5.5 nm\) (4.2 K), a bulk current polarization of 22% in the Py electrodes at 4.2 K is obtained: \(\alpha_F \approx 0.22\). These values are in the same range as the results obtained from the analysis of the GMR effect9,10,17,18,24.

With the obtained parameters we can calculate the maximum current polarization \(P = I_F - I_D/I_F + I_D\) in the Cu wire. For the samples with the smallest Py electrode spacing we obtain \(P \approx 2%\) at 4.2 K. When we scale the observed signals to the device crosssections, we find that the scaled spin-valve signal of refs 13 and 14 is typically four orders of magnitude larger than ours. This contrast
corresponds with the need to invoke a spin polarization of the current in the normal metal of about 100%, to explain the results of refs 13 and 14 in terms of spin accumulation. In our opinion this must imply that the observed effects of refs 13 and 14 cannot be related to spin accumulation.

We have thus demonstrated spin injection and accumulation in a mesoscopic spin valve. We find a surprisingly long spin-foil length in Cu of around 1µm at 4.2 K and around 350 nm at room temperature. For the smallest Py electrode spacing, the magnitude of the spin signal and the current polarization P in the Cu wire are limited by the unfavourable ratio of the spin-independent resistance of the Cu strips (Liσ0) and the spin-dependent resistance of the Py ferromagnet (Liσp). In principle, larger signals can therefore be obtained by a proper choice of materials and geometries.

Finally we note that our system permits the study of spin transport phenomena, such as controlled spin precession in solid state devices and the control of spin-polarized currents at room temperature by additional ferromagnetic contacts.10

Acknowledgements
We thank H. Boeve, J. Das and J. de Boeck at IMEC (Belgium) for support in sample fabrication, M. S. Nijboer for experimental assistance and T. M. Klapwijk for discussions. We wish to thank the Stichting Fundamenteel Onderzoek der Materie and the EU project SPIDER for financial support.

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Shear-induced molecular precession in a hexatic Langmuir monolayer
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Liquid crystalline behaviour is generally limited to a select group of specially designed bulk substances. By contrast, it is a common feature of simple molecular monolayers and other quasi-two-dimensional systems, which often possess a type of in-plane ordering that results from unbinding of dislocations—a ‘hexatic’ liquid crystalline phase. The flow of monolayers is closely related to molecular transport in biological membranes, affects foam and emulsion stability and is relevant to microfluidics research. For liquid crystalline phases, it is important to understand the coupling of the molecular orientation to the flow. Orientationally ordered (nematic) phases in bulk liquid crystals exhibit ‘shear aligning’ or ‘tumbling’ behaviour under shear, and are described quantitatively by Leslie–Ericksen theory. For hexatic monolayers, the effects of flow have been inferred from textures of Langmuir–Blodgett films1–10 and directly observed at the macroscopic level10. However, there is no accepted model of hexatic flow at the molecular level. Here we report observations of a hexatic Langmuir monolayer that reveal continuous, shear-induced molecular precession, interrupted by occasional jump discontinuities. Although superficially similar to tumbling in a bulk nematic phase, the kinematic details are quite different and provide a mechanism for domain coarsening and eventual molecular alignment in monolayers. We explain the precession and jumps within a quantitative framework that involves coupling of molecular orientation to the local molecular hexatic ‘lattice’, which is continuously deformed by shear.

The interfacial thermodynamics and rheology of molecular films like Langmuir monolayers are responsible for the stability of multilayer materials such as foams and emulsions11. They are important model systems for studies of dynamics and molecular interactions in bio-membranes and, as quasi-two-dimensional systems, display a variety of unusual liquid crystalline phenomena. The application of synchrotron X-ray scattering and specialized imaging techniques such as fluorescence and Brewster angle microscopy (BAM) have