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Magnetoresistance in nanocontacts induced by magnetostrictive effects

M. Gabureac,[1] M. Viret,[1,*] F. Ott,[2] and C. Fermon[1]
[1]*Service de Physique de l'Etat Condensé, DSM/DRECAM-CNRS URA 2464, CEA Saclay, F-91191 Gif-Sur-Yvette cedex, France*
[2]*Laboratoire Léon Brillouin, CEA/CNRS UMR 12, CEA Saclay, F-91191 Gif-Sur-Yvette cedex, France*

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Nickel atomic contacts made with the break junction technique have been subject to a magnetic field while monitoring their resistance. Large resistance changes with the angle between the applied field and the contact direction can be explained by modifications of the contact geometry induced by magnetostriction.

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The effect of a field on the resistance of nanometer-sized ferromagnetic contacts has attracted a lot of attention lately with the reports of extremely large effects.[1,2] Several groups have reported orders of magnitude resistance changes, either positive or negative, when a field is applied on a ferromagnetic constriction. Theoretical models have also been established[3,4] to explain the effect, which rely on the reflection of electronic wave functions on a constricted domain wall. The idea is that when the conduction electrons are confined in a one-dimensional channel, transverse modes are constrained by the boundary conditions leading to a limited number of transmitted longitudinal modes. The conductance is then expected to depend on lateral dimensions in a nonmonotonous way, showing quantization properties when the constriction is narrowed down to the scale of the Fermi wavelength. This physics is well known for semiconductors where it has been intensively studied in two-dimensional electron gases. Most of the conductance measurements can be explained in the frame of the Landauer-Bütticker theory which describes electronic transport through a finite number of channels. When a large field is applied, or when the material is ferromagnetic, the spin degeneracy is lifted and the electronic channels become spin polarized. This simple picture leads to the establishment of half-metallic transport when a single conduction channel is opened in the nanostructure. Moreover, in ferromagnets, domain walls (DW's) are expected to be sensitively narrowed in constrictions[5,6] and the change in transmittivity they induce can be calculated. When an atomically thin domain wall is introduced in a single channel contact, the conductance is expected to drop to zero.

However, this simple picture is complicated by the fact that the vast majority of magnetic systems under study are metals with Fermi wavelengths around 3 Å. On the transport side, this implies that the realization of a single conduction channel could only be achieved in constrictions of one single atom. It is also known that in that case, the overlap of atomic orbitals produces more than one conduction channel.[7] Hence, full polarization is unlikely to be obtained. Furthermore, magnetic configurations at the atomic level are complicated and cannot be measured. The shape of a "domain wall" in structures of atomic size can probably not be considered a sharp interface. All these effects should significantly reduce the magnetoresistance in nanocontacts.

Apart from problems related to electronic transport in ferromagnets in reduced dimensions, more worrying effects have long been eluded in this field, namely, magnetomechanical effects. It has been known for a long time that the action of an external field on ferromagnetic materials induces forces which lead to displacements and distortions. Even when magnetic parts are not allowed to move, a phenomenon known as magnetostriction[8] tends to distort ferromagnets in directions linked to their magnetization. This stems from spin-orbit coupling and it can be simply quantified for polycristalline (isotropic) materials:

$$\Delta\ell/\ell = \tfrac{1}{2}\lambda_s(3\cos^2\theta - 1),$$

where $\Delta\ell/\ell$ is the strain measured at an angle θ from the magnetization direction and λ_s the anisotropic saturation magnetostriction coefficient. The latter can be either negative or positive. This simply describes the distortion associated with the magnetization direction in a saturated sample. Although the effect in simple ferromagnets is small (in the ppm range), it is likely to affect the cross section of two electrodes in contact. For instance, a small Ni magnet of 100 μm in diameter shrinks in the direction of its magnetization by 5 nm, which can be enormous at the scale of an atomic contact. In this Rapid communication, our aim is to demonstrate the ability of magnetoelastic effects to change the geometry of nanocontacts and hence to affect significantly their resistance. Because magnetostriction is attached to the magnetization direction, any resistive effect should be visible when a saturating field is rotated in the plane of the contact.

The nanocontacts were elaborated using the break-junction technique[9] where a 100 nm wide, 1 μm long bridge is defined by electron-beam (e-beam) lithography onto a polyimide layer. In our case, we used kapton (=polyimide) as the substrate on which we spun a 2 μm thick polyimide layer in order to improve the smoothness. Then, 20 nm of Ni is deposited and lifted off in an *maa*/*pmma* bilayer on which the pattern had been defined by *e*-beam lithography. The polymer is then etched isotropically by reactive ion etching which undercuts below the Ni structure. The end result is a suspended bridge attached to two electrodes of different shapes presenting two distinct coercive fields (although this property is not a requirement for the conclusions of this paper). The chosen geometry is the one in which a yoke-type electrode is linked to an elliptical electrode through a 300 nm wide constriction as shown in Fig. 1. One can then bend the substrate with a micrometer screw fitted in a cryostat where a 2 T field can be applied. In this geometry, the ferromagnetic

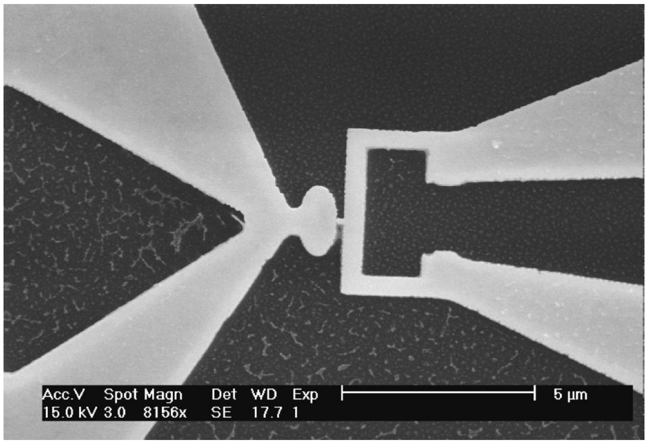

FIG. 1. Scanning electron micrograph of the break-junction geometry. The two electrodes on both sides of the bridge have different shapes in order to reverse at distinct coercive fields.

thin film is fully attached to the substrate except for the bridge which is suspended. Hence, during bending, the two sides of the bridge are pulled apart and the resistance is continuously monitored in a constant voltage mode with an ac measurement technique. This setup is particularly stable and it is possible to mechanically stabilize the contact with a precision estimated below the picometer. When a magnetic field is applied, magnetostriction will affect the suspended bridge, but will not influence the rest of the structure because it is tightly attached to the polymer. The sample is also clamped at both edges in order to eliminate a possible bending due to magnetostrictive forces. Hence, only the suspended region will be affected by the strain resulting from the change of external magnetic field. Because we are using *e*-beam lithography, these suspended regions can be reduced below 1 μm. We would like to point out here that, due to the break-junction geometry, magnetoelastic effects are, in a way, minimized. Nevertheless, we will show that not only can we measure them, but their consequences on the transport can also mask any other—magnetoresistive—effects.

The measurements are carried out at room temperature where the bridge is first elongated until it breaks. The two halves are then brought back together and the transport goes from tunneling to contact when the first atom bridges the two electrodes.[7] When the contact is closed further, the conductance varies in a noncontinuous manner showing jumps as the atomic configuration of the contact changes. One can then go back and forth breaking and closing the contact while measuring the conductance. Because of the exceptional precision of the technique, it is possible to stabilize the electrodes in the tunneling regime with a 4 Å gap, for example, and then bring them back together and study the atomic contact regime. In tunneling, because the resistance is exponentially dependent on the distance between electrodes, any length change results in a measurable signal. In this configuration, the junction works as a very sensitive (one-dimensional) position sensor. In order to observe the effect of the anisotropic magnetostriction, the tunneling resistance was monitored while a 1 T field was slowly rotated in the plane of the structure. The measured effects depend sensitively on the underetching, i.e., the distance over which the bridge is suspended. This has been varied by changing the reactive ion etching time and controlled using the scanning electron microscope. Figure 2 shows the effect obtained in a Ni sample where the bridge is underetched by about 2 μm. The resistance varies by more than an order of magnitude in a periodic fashion.

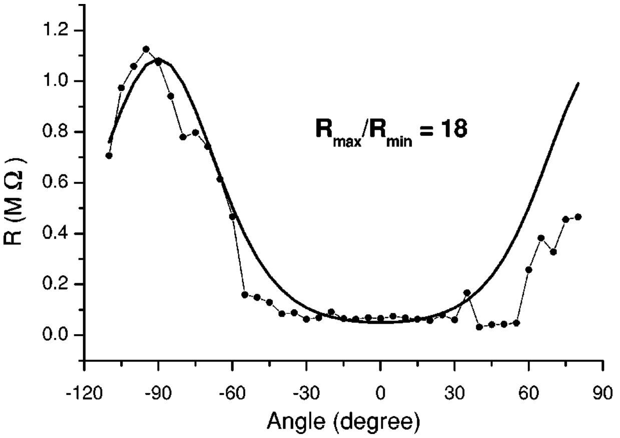

FIG. 2. Dependence of the tunneling resistance with the magnetization angle. The experiment is carried out rotating an in-plane saturating field of 1 T on a sample underetched by 2 μm.

One can then quantify the expected magnetostrictive effects which open or close the gap. Figure 3 gives a schematic of the junction geometry. In the hypothesis where the magnetic thin film is everywhere attached to the polymer on which it has been deposited, only the suspended parts of the bridge (on a distance u) are affected by length changes. As the field is rotated, this results in a modification of the gap given by

$$\Delta d = -\frac{1}{2} u \lambda_s (3\cos^2\theta - 1).$$

This leads in turn to a resistance change given by

$$R/R_0 = \exp(-\Delta d/d_0) = \exp\left[\frac{1}{2} u \lambda_s (3\cos^2\theta - 1)/d_0\right],$$

where d_0 can be extracted from the slope in the ln(R) vs gap obtained pulling the bridge or coming back in contact. The solid curve in Fig. 2 is the resistance variation expected with the previous expression and an underetch of 2 μm. In that case, the gap closes by 1 Å during magnetic-field rotation.

The influence of the magnetoelastic effect on the resistance is obviously largest in the tunneling regime where the resistance depends exponentially upon the distance between electrodes. It can also be lowered by minimizing the etching

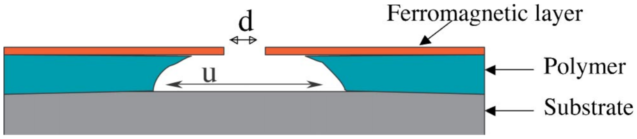

FIG. 3. Schematic of the junction geometry. The underetching is the relevant length scale for the magnetostrictive effects.

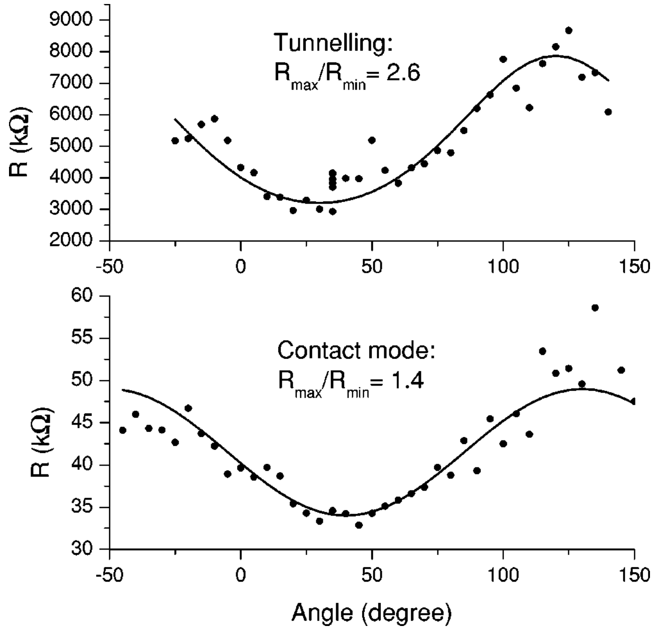

FIG. 4. Comparison of resistance changes in the tunneling and atomic contact regimes in a sample with an undercut of 650 nm. The offset angle is caused by the exact geometry of the atoms of the contact which directly affect the current direction. Note that this offset changed between the two geometries.

under the bridge. We have made a sample where the undercut is reduced below 1 μm in which we measured the resistance dependence with field angle. It is interesting to see how the resistive behavior changes in the atomic contact mode. The resistance was first stabilised at 4 MΩ (corresponding to a 6 Å gap) for a series of measurements, and then the two arms of the bridge were brought back together until the first jump to contact was observed. This was obtained for a resistance of 38 kΩ, which is likely to correspond to only two atoms touching.[10] The measurements as a function of field direction are shown in Fig. 4 where one can see that the effect is larger in tunneling where the resistance changes by a factor of 2.6, while the change is "only" of 1.4 in contact mode. The solid curve in the tunneling measurement is the expression of the resistance variation due to magnetostriction with an undercut of 650 nm. This corresponds to the gap closing by 0.3 Å. In contact mode, such a displacement is likely to change the orbital overlap between the two atoms of the contact, hence affecting the resistance. It is worth mentioning here that often the resistance changes in this regime are irreversible. This could be due to an atomic rearrangement at the contact level, but this is not observed systematically (the measurement shown in Fig. 4 is reversible).

Obviously, these magnetoelastic effects are undesirable when studying magnetoresistance in nanocontacts. Unfortunately, they seem to be unavoidable in most experiments. We would like to point out here again that the break-junction technique tends to minimize free standing parts which are affected by strain. Indeed, in many other experiments, such as, e.g., electrodeposited contacts, the size of the ferromagnetic parts can reach microns for which adherence to a nondeformable surface (if present) cannot be sufficient to get rid of field induced distortions of the electrodes themselves. Depending on the exact geometry of the contacts, a slight motion of the electrodes can have a dramatic effect on the contact area and hence the contact resistance. One other way of avoiding the effect would be to make sure that the magnetization reverses only by changing its sign, but not its direction. Magnetostrictive effects being even, no deformation would occur. In fact, our chosen electrode shapes aim to achieve such an ideal magnetic switching. Even with these precautions, one still gets anisotropic effects as shown in Fig. 5 where $R(H)$ curves as a function of applied field for different field angles are presented. One can see that the MR effect is either positive or negative with a general shape dominated by anisotropic effects.

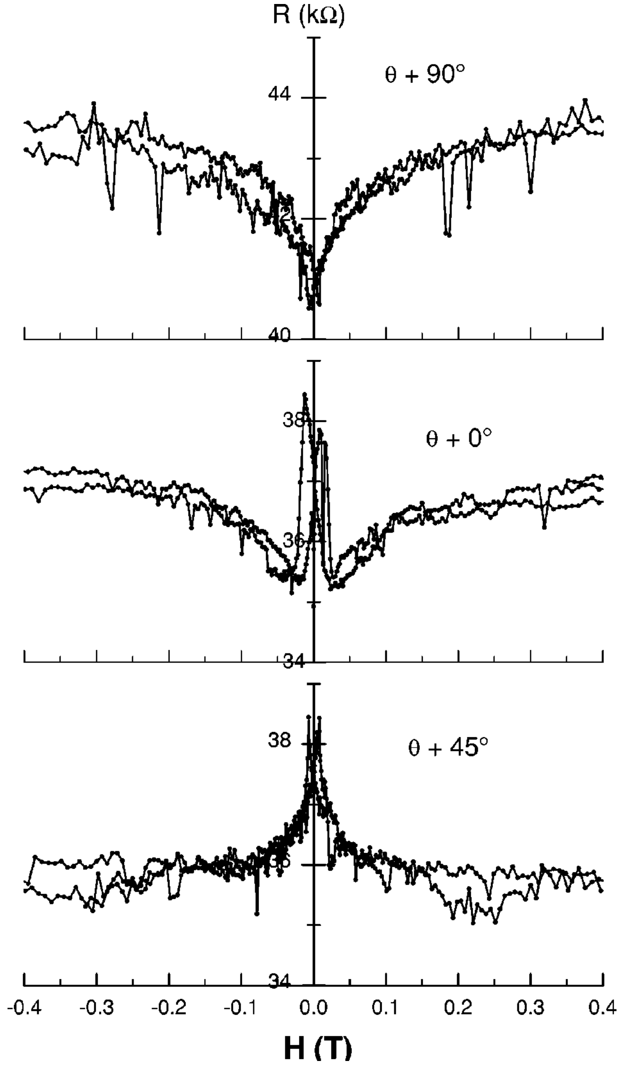

FIG. 5. Magnetoresistance curves at different angles between applied field and the edge of the sample (θ is an offset angle depending on the exact contact geometry). This behavior can be understood as a consequence of the anisotropic magnetostriction changing the contact cross section.

In order to isolate resistive effects coming from spin polarized transport, one can try to optimize the reversal so that the magnetization on both sides of the contact remains along the same direction while reversing. The break-junction technique allows us to validate the measurements as regard to geometrical changes, by measuring first in the tunneling configuration. Then, one knows what displacement to expect in the contact regime. We have previously used this procedure to extract meaningful data regarding MR in atomic Ni contacts.[11] Perhaps, the ideal geometry for nanocontact magnetoresistance measurements is the one obtained when a tiny indentation is realized in an insulating membrane separating two films. In such systems, MR effects have also been measured small,[12] but atomic sizes have not yet been achieved.

In conclusion, we have evidenced here the importance of magnetomechanical effects in measuring magnetoresistance in nanocontacts. These effects are extremely difficult to avoid and, in most cases, large resistance changes are due to mechanical modifications of the contact geometry. We suspect that many reported ‘‘giant’’ resistive effects result from simple field induced magnetomechanical distortions. We suggest that a good way of validating MR measurements in nanocontacts would be to verify that the resistance remains constant when a saturated field is rotated in the plane of the contact.

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*Electronic address: mviret@cea.fr

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