Magnetoresistance and magnetostriction in magnetic contacts

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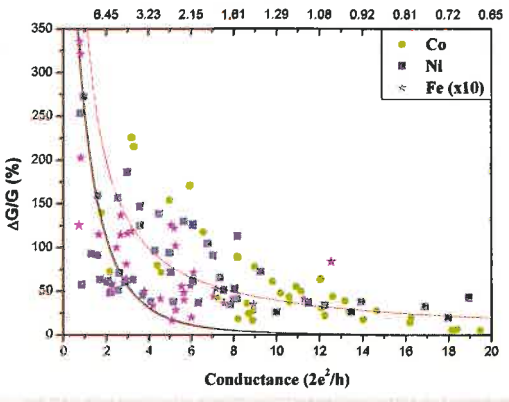
Ballistc magnetoresistance in atomic and nanometer size electrodeposited contacts

Ballistic magnetoresistance (BMR) in point atomic contacts with resistances (R) larger than around 1000 Ω exhibits very large values, up to 500% [1-4], while the general trend is that BMR increases when R decreases. This BMR is the resistance that the electric current manifests through a point contact when a magnetic field is applied. The cause of this phenomena is explained in terms of domain wall (DW) scattering in magnetic materials [2,5], assuming that the DW width formed at the contact is of the order of the contact size. If the DW is narrow, strong non-adiabatic scattering with spin conservation at both sides of the contact is predicted by an old theory of Cabrera and Falicov [5], applied to atomic contacts by Tatara *et al.* [2]. The BMR can be expressed by:

$$BMR(\%) = \pi^2/4(\zeta^2/1-\zeta^2)F(\xi) \qquad (1)$$

The factor F is a dynamic term that reduces BMR according to the DW width and shape, and describes the adiabaticity in the spin electron transfer from one side of the contact to the other. The rest of eq. 1 is the ratio of the difference in the density of states between majority and minority spins at the Fermi level in the electrodes at both ends of the contact. This is basically the Julliere formula [6] for two electrodes made of same metal. The resistance is spin ballistic if the contact is small and the spin mean free path (l) is larger than the contact size.



▲ Fig. 1: Magnetoconductance as a function of the contact conductance (bottom x-axis) and the contact resistance (top x-axis) for Ni, Co and Fe contacts. Black and red are the theory line approximations in the limits of a small and large number of conducting channels, respectively.

The resistance can be estimated assuming that one atom at the contact provides a conducting channel, and that one atom takes a surface area of approximately 0.1nm² by:

$$R(\Omega) = 12900\ \Omega / (10\ a^2\ (nm^2)) \qquad (2)$$

where 12900 Ω is the quantum of resistance, and a is the size of the contact in nm. The above formula is basically Sharvin's formula for ballistic transport [7]. The typical values from (l) for the spin mean free path are 30-50nm, and it therefore can be observed from the above formula that the limit for ballistic transport are in R values larger than 1Ω. For much smaller values of R the classical Maxwell formula controls the resistance that becomes non-ballistic. Fig.1 shows BMR values for Ni, Fe, and Co as a function of the conductance expressed in quantum units. The resistance of the contact is obtained simply by dividing the quantum of resistance 12900 Ω by the number of conducting channels (given in the upper x-axis). Fig.1 indicates that, for example, for 20 channels, corresponding approximately to 2 nm² of contact area, the resistance is 600 Ω! By then, the BMR is largely reduced to a 10% value of that for one channel of conductance. This conforms very well with theory, as indicated by the good agreement between the lines (theory) and dots (experiment) in the Fig 1. While this observation may produce very interesting physics from the point of view of theory and experiments, it does not qualify for technological applications because the contacts are unstable and last only a few minutes.

To overcome this problem and improve the stability of the contacts, we have electrodeposited contacts in magnetic and non-magnetic wires and films, forming a "T" configuration. To our surprise, we have observed even larger values of MR; up to 700% in Ni contacts deposited on small gaps between Ni wires [8] with typical R-values of 5-20 Ω. These MR values clearly cannot be explained by DW scattering [9], since the contact sizes are of the order of 10 nm, while the DW scattering [2,5,9] yields BMR values not larger than 10%. Recently, much larger values (many thousands per hundred!) of MR have also been claimed [10,11]. This effect of large BMR values in 10 nm size contacts may be assigned to the formation of a very thin "dead layer" or non- stoicheometric compound (oxide, sulfite, etc), at the nanocontact region that may reconfigure the spin density of states defining the electron transport [11,12]. While the very large values are very difficult to reproduce and to stabilize, we have been able recently [13] to obtain very stable contacts with highly reproducible R(H) curves; i.e., variations of resistance versus applied magnetic field H.

These last recent magnetic contacts were formed with two films of Cu as a substrate, separated by a gap between 100 and 2 μm wide that we can create with electrodeposition techniques, Fig.2a. Once the desired gap is created, we deposit the magnetic contact. This material may be Ni, Fe, Co or whatever as well as binary compounds such as Permalloy $Ni_{85}Fe_{15}$, which is very soft and has a small coercive field. With this procedure we have obtained extremely stable and reproducible R(H) curves that can last for the duration of thousand of loops. As an example, Fig.2b shows the reproducibility of the R(H) curves, for only some tens of the hundreds of curves that have been measured. The reproducibility is astonishing and is encouraging for the development of highly sensitive sensors as magnetic reading heads. At present we can obtain these kinds of results with a yield of 60% out of the thousands of samples we have studied. The BMR values, obtained with the typical reproducibility given in fig.2(b), range between 20% and 300% for contacts of the order of 10 Ω that correspond to contacts of approximately10nm in size.

Magnetoresistance of the deposit controls its morphology and structure

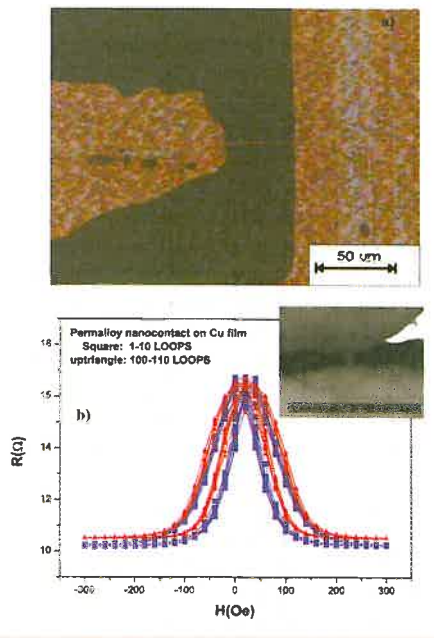
To prove the magnetoresistive effect we have performed electrochemical experiments applying a magnetic field during deposition. The idea goes as follows:

a) We grow Ni by electrodeposition with zero applied fields at several anodic potentials.

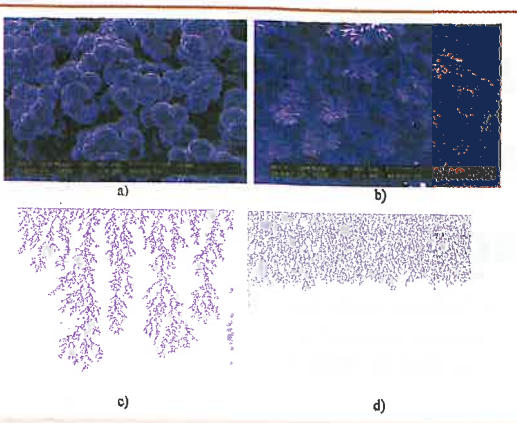
b) We, subsequently, make the same experiments with an applied magnetic field using weak fields up to 500 Oe. This field is approximately the coercive field of the Ni electrodeposits as we observed in our BMR experiments on nanocontacts (see Ref.8). This is not, however, to be confused with Fig.2(b) where the coercive fields are much smaller because in the latter case the deposit is permalloy and has a 25 Oe coercive field.

c) The field is applied in the direction perpendicular to the deposit plane in such a way that the cross product $\mathbf{H} \times \mathbf{v} = 0$ ($\mathbf{H}$ and $\mathbf{v}$ being the applied field and the velocity of the ions in the electrochemical solution, respectively). In other words, no Lorentz force exists, and thus no surface smoothing effects are expected [13, 14]. In fact, the only gradient effects that are expected should be weak due to the small fields that were applied, (500 Oe maximum).

d) Under these conditions no important effects were expected [13,14]. We discovered, however, very large effects due to these subtle small fields. We attribute these to the resistance of the deposits without field and with field. This resistance should be small for applied field due to magnetoresistive effects. When the field is applied the DW's are removed- as already discussed- and the resistance decreases.



▲ Fig. 2: a) Optical microscope photograph taken near the contact area of the "T" configured Cu film arrangement. b) BMR curves of deposited permalloy contacts on Cu film. We measured the sample twice, taking one hundred loops per measurement. Indicated here are the first ten loops of each measurement: the upward-pointing triangular data points depict loops 1 through 10, while the square data points depict loops 100 through 110. The inserts at the top right of the curve depict SEM scans corresponding to the contacts referred to with the scales shown at the bottom of the photos.



▲ Fig. 3: SEM microphotographs of nickel deposits obtained at a cathodic potential of -1300 mV/SCE from a Watt plating solution with the addition of coumarin: a) without and b) with a perpendicularly oriented magnetic field of 500 Oe; and the result of simulation of a cluster growth on the surface for c) k_1=1 and d) k_1=5.

In Fig.3a we show experiments revealing SEM micrographs of the deposits of Ni on Cu for an anodic potential of –1300mV/SCE with no field. The observed structure here is made of an aggregation of clusters. However, when a field H = 500 Oe is applied in the direction that the ions in the solution move, we observe an arboreous dendritic structure of long branch formations similar to that of sea algae (Fig.3(b)), which is completely different to that of the case when H = 0 (Fig.3a). This is due to the fact that when the field is 500 Oe the resistance is smaller than that for zero field applications, because the DW's have been removed. In the zero field case, on the other hand, DW's are present and contribute to the resistance. The effective anodic potential between the end of the filamentous deposits and the calomel reference electrode is smaller for zero fields due to the larger resistance of the filaments, which does not allow them to grow. Notice that the growth reported here does not have the form of needle-like structures [15], but has the form of a bead-arboreous-dendritic structure; i.e. the filaments have the form of a rosary formed by beads and the filaments do not have any special orientation depending on the applied field. This is at variance with the needle- like structure observed in the deposits of Fe at 2000 Oe fields [15]. In addition, the field does not affect the growth of Cu because this is non-magnetic.

This idea is illustrated by a computer simulation using the diffusion limited aggregation (DLA) model [16,17]. Fig.3c is a simulation considering that the filaments resistance is zero and then an arboreous dendritic structure is obtained for the deposit in agreement with Fig.3b and the discussion above. However, when the resistance of the wires is taken into account the structure is more compact as described in Fig.3d, which correlates well with Fig.3a. These experiments, therefore, show how a subtle magnetic field can provide a gracious and different kind of structure. As in nature, the processes are mostly electrochemical, and it just might be that many natural forms could be influenced by subtleties of the surrounding stray magnetic fields.

Magnetostriction measured with an atomic force

One of the problems raised while measuring the variation of the resistance with the applied magnetic field in small contacts is: *how much variation of the resistance may be due to change of the contact during the application field because of the accumulated magnetoelastic energy or magnetostriction?* This is a difficult problem to solve and in order to do it we have established a new method, that is elegant

and educational at the same time, using a local probe; i.e., scanning tunnelling microscopy (STM), atomic force microscopy (AFM), etc. We illustrate it below with the case where we use an AFM.

To observe magnetostriction under the AFM, we place the sample between the poles of a magnet where we can vary the field without moving the magnet itself. An electromagnet is ideal for this application. A schematic diagram of the set up is shown in Fig.4a. While the tip is scanning the surface (typically an area less than a thousandth of a millimetre), the field is activated by turning on the current to a value corresponding to whatever magnetic field strength we desire. The results are instantaneous, and quite illustrative of the process in action. The sample (typically a wire during our first measurements) was glued to the sample holder on one end, while scanning occurred at the other (see Fig.4b). In this way we could for example observe the change in the wire's length when the direction of scan was aligned with both the direction of the magnetic field and the length of the wire. After consecutive field applications the result would be a picture such as shown in Fig.4c. In this case contraction is movement to the left, and expansion to the right. What is interesting is that depending on the rate of scanning (typically less than a second per line for slow scans), the tip/sample contact is disrupted for a few lines, but then stabilizes immediately after the magnetostriction effect is completed. Even more important, when the field is removed the picture moves precisely back to its original position as if nothing ever happened. We can measure the shift by taking any features immediately before the field is applied and measuring the distance to the same features after field application. Our results invariably agree with other methods of measurement, yet only this technique provides valuable topographic information of the shift itself on the nanoscopic level.

The method is simple, direct and illustrative in a visual manner of a phenomenon only previously measured indirectly, and its potential is endless with applications ranging from nanotechnology and nanocircuitry to the exploration of new magnetic materials and even with possible extensions in biology. Besides technological applications the direct observation of magnetostriction holds the potential to expand the understanding of the relationship between mechanical and magnetic properties of materials, and may even lead to the observation of magneto-mechanical phenomena on the atomic level.

Using this method we have measured the possible displacements or motions of the contacts that give rise to the large BMR depicted in Fig.2b with substantial reproducibility. Within our resolution in the measurement (1 nm), we see no motion whatsoever of the contacts. That implies that if there are displacements they must be much smaller than 1 nm because we do not see any instability whatsoever in the AFM tip when the magnetic field is applied. Therefore, this tends to indicate that the observed values result from magnetoresistance with a high degree of reproducibility. If this is the case, these contact devices clear new ground for very sensitive sensors, especially as reading heads for reading magnetic information compacted in the Terabit/inch^2. At present research is going on in miniaturization and stabilization over weeks of the electrodeposited contacts.

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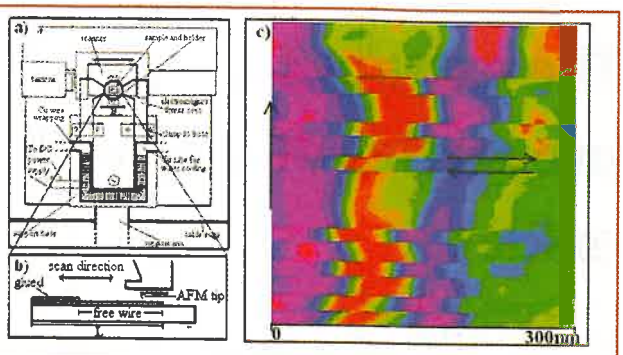

▲ **Fig. 4:** a) Top-view schematic of our setup for the AFM magnetostriction measurement. The sample is depicted in the bold circle between the two poles of the electromagnet and under the scanner. The double arrow marked B indicates the direction of the magnetic field. b) Side-view zoom of the sample configuration, including the AFM tip situated at the bottom of the scanner. The samples were metallic wires, glued on one end, while scanning occurred as close to the free tip of the wire as possible. c) A typical topographic image, of area 300 nm x 300 nm, which results from a tip scan along the length of the wire. The corresponding wire length is from left (toward glued portion) to right on the scan, while the scan itself is moving in the direction of the vertical arrow (bottom to top). The material used is a permalloy (an alloy of nickel and iron), and the length of the wire is about 10 mm. Application of a field causes a linear shift in the whole picture to the left, that indicates contraction, whereas on removal of the field the image moves to the right, and the wire expands back to its original position (see corresponding horizontal arrows). The shift itself was measured at 11 nm for the field strength applied.

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