Magnetoresistance in excess of 200% in Ballistic Ni Nanocontacts at Room Temperature and 100 Oe

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We present magnetoresistance experiments in magnetic Ni nanocontacts in the ballistic transport regime at room temperature. It is shown that the magnetoresistance for a few-atom contact reaches values of 280% at room temperature and for applied magnetic fields of 100 Oe. Results are presented for over 50 samples showing the trend that the smaller the contact the larger the magnetoresistance response. This indicates that the effect arises just at the nanocontact. [S0031-9007(99)08850-X]

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Giant magnetoresistance (GMR) is a field of great interest because of its technological applications. GMR was discovered in magnetic multilayers [1,2], but since then other compounds and systems such as heterogeneous AgCo and CuCo granular alloys [3–5] have also shown GMR opening new expectations in magnetic technologies. The multilayers and the granular alloys have in principle different topological systems but nevertheless showed similar GMR values: 200% and 5% approximately at 4 K and room temperature (RT) using fields of 0.5 to 30 kOe. Also "colossal" magnetoresistance has been observed in manganite perovskites [6–10] with magnetoresistances over 400% at 4 K and 15% at RT using fields of several 10 kOe.

There have also been magnetoresistance (MR) studies in very thin Ni wires of 30 nm diameter with values of the MR of 8% at 1–10 K and a 2 kOe field [11]. Theoretical studies [12] have tried to explain this effect as due to domain wall scattering that contributes to the decoherence of electrons. However nobody has studied what happens with the MR in magnetic nanocontacts showing conductance values of a few conductance quanta $2e^2/h$, where e and h are the electron charge and the Planck constant, respectively. In the past few years we have been working on the conductance properties of nanocontacts that showed conductance quantization [13–15]. There are also experimental results in magnetic nanocontacts with some indications of magnetic influence in the conductance [16].

In this work we present experiments for the MR of Ni nanocontacts, i.e., contacts in the ballistic regime with a few conductance quanta that show MR values up to 280% at RT and 100 Oe applied magnetic fields for a few-atom contact and decrease as the contact area increases.

In order to proceed we have devised the experimental setup shown schematically in Fig. 1. A cell is built in which two nickel wires of 2 mm diameter ended by rounded tips are put into contact facing each other. A force is applied at the end of the wires until a current flows between the nanocontact formed at the tips when a bias is applied. This is nanocontact size, i.e., a few-atom size (see the schematic view of the nanocontact in Fig. 1) because it supports a few conductance quanta. The wires are tightly bound to a Teflon tube by resin in such a way that gives rigidity to the sample, and that a large force is needed to displace them. The wires have two coils at the end of them to produce magnetic fields. If no current is applied to the coils then the current monitored in the oscilloscope, as a function of time, is constant. However, if in coil 1 a direct current produces a magnetic field that orients the magnetization on the wire axis, and in coil 2 an oscillating square current alternates the orientation of the magnetization in the wire where coil 2 is acting, then the current monitored in the oscilloscope has large fluctuations associated with the reversal of the direction of the magnetic field in phase and antiphase with the one in the first wire. In other words, the oscillating field in the wire creates the parallel and antiparallel states of magnetization that give rise to MR. To present more information on the state of the magnetization under the applied field we have measured the hysteresis loops of the wire (top-left inset in Fig. 1) by measuring the induced potential for a sinusoidal current at 10 Hz on coil 2.

In Fig. 2, we show the experimental results with Ni nanoconstrictions; notice that in Fig. 2a the current fluctuates by a factor of 3 when a field of 20 Oe is produced by the coils. This represents a magnetic response in conductance of $\sim$300% at RT and for a 20 Oe applied field. This is the maximum value that we have observed but it is not the general case because the MR may depend on the particular spin configuration and density of states at the Fermi level just at the nanocontact. In Fig. 2b we show MR results for over 50 samples with a different size of nanoconstriction, and different conductances illustrating that the magnetoresistances for the smaller nanoconstrictions (lower conductance level) are usually larger than those for the bigger nanoconstrictions (higher conductance level). This is a general trend observed in the data (Fig. 2b).

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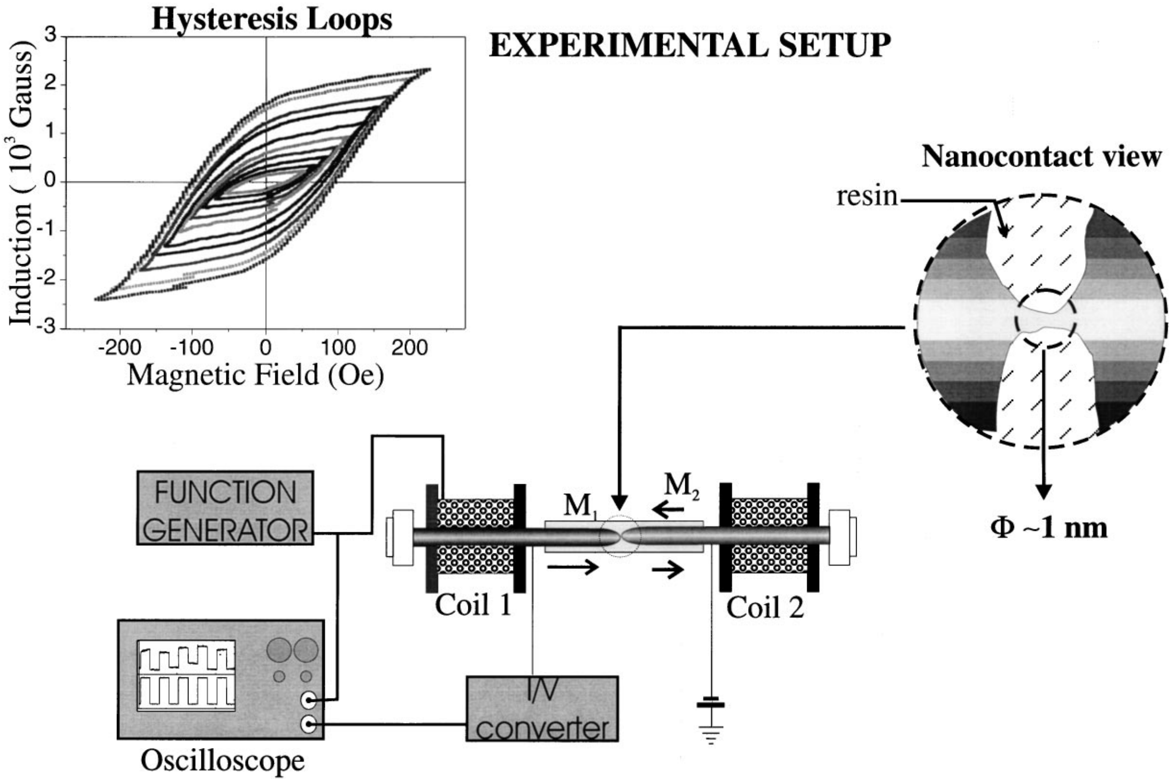

FIG. 1. Scheme of the experimental setup used in this work: two wires ending with rounded tips face each other and, under pressure, form a nanocontact (top-right inset, not scaled with the size of the wires). A bias is applied to produce a current measured in the oscilloscope via an I-V converter. Two coils are used to produce the magnetic fields. The hysteresis loop of wire 2 measured using a 10 Hz current in coil 2 is presented in the top-left inset.

To further explore the importance of magnetic-magnetic contact in the MR response we have performed experiments with magnetic-nonmagnetic contacts. In contrast with the above case, Ni-Cu, Cu-Cu, and Ni-thin Cu-Ni nanoconstrictions give rise to no effect at all when the experiments are performed under the same conditions as that for the Ni-Ni case (see Fig. 3). Notice that for the case Ni-thin Cu-Ni (Fig. 3c) the Cu thickness is 0.1 mm. To give further evidence that the fluctuations in the resistance are real we find that not only a square wave but also a triangular and sinusoidal wave manifest the effect. In Fig. 4a we present the conductance fluctuations for a sinusoidal wave and observed a saturation in the MR (in magnetization) for a 50 Oe applied field. Also a small Ni tip (0.5 mm length) in the junction Cu-small Ni-Ni shows magnetoresistive effects of the order of 40% (Fig. 4b). In both cases the alternating current has been chosen to illustrate the effect of parallel and antiparallel magnetizations in the wires. This shows that only the Ni-Ni contacts are responsible for the variation in conductance and for nonmagnetic-magnetic contacts no MR is observed.

It is legitimate to argue that the variations in conductance observed could be assigned to the change of the nanocontact caused by magnetostriction. This is always difficult to discern but we believe, with all our precautions, that the experimental facts do not favor a magnetostrictive explanation: First, with our design of the experimental setup the possible magnetostrictive force should be effectively eliminated by tightly embedding the nickel wires in the Teflon tube and, further, by the pressing force at the end of the wires since nickel has a negative magnetostriction; second, magnetostriction force depends on the square of the magnetization and for the square waveform the magnetostriction stresses are the same for the positive and negative fields, therefore the high and the low resistive states cannot be magnetostrictive; finally, and most important, if one nickel wire is replaced by copper then there is no effect at all as already shown in Fig. 3a. The same is true if the two wires are nickel but in between them we insert a thin copper wire of 0.1 mm diameter so that the nanoconstriction is Ni-Cu (Fig. 3c). In this case the magnetostriction is the same as for Fig. 2a but no change in conductance is observed. Analogously magnetostatic forces [17] may also be ruled out as responsible for contact modification because these are the same in the cases of Figs. 2a and 3c [17] and only the contact Ni-Ni (Fig. 2a) shows conductance oscillations. Also in the case of Fig. 4b the magnetostatic force is zero in first approximation [12] and nevertheless shows oscillations in conductance.

Finally we would like to present some theoretical discussions to explain our experiments. These show the influence of the magnetic state in the proximity of the two

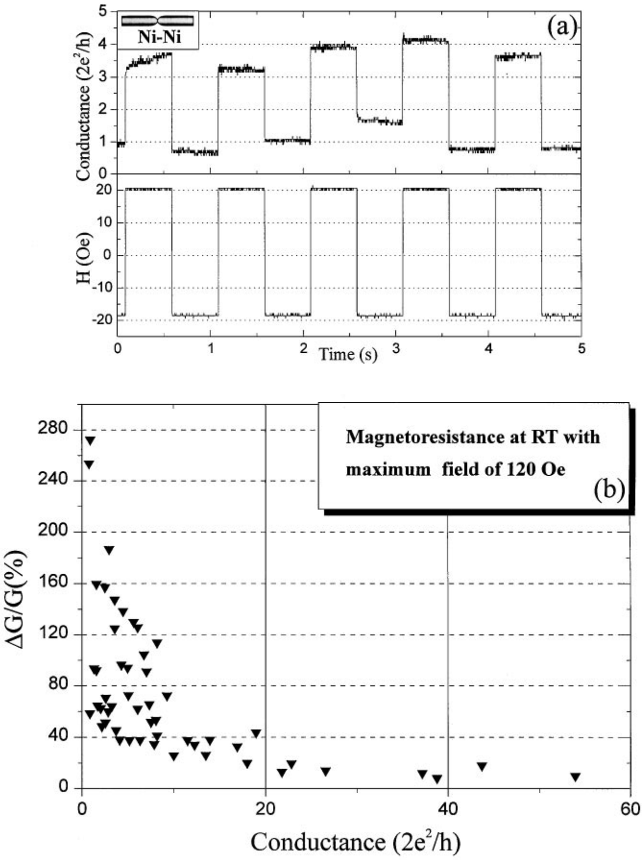

FIG. 2. Measurements on Ni-Ni nanoconstrictions. (a) Two nickel wires of millimeter radius are used to form nanoconstriction. (b) Dependence of magnetoresistance on the conductance level: the applied magnetic fields range from 20 to 120 Oe. Notice that the smaller the conductance the larger the magnetoresistance.

wires and of the width of the magnetic domain wall at the nanocontact. The value of the MR depends critically on the spin configuration just at the contact, because of the following: The upper left inset of Fig. 1 represents the hysteresis loops of the global magnetization in the wire but it does not tell us the spin configuration at the very ends of the contact. Notice that the same global loop of magnetization provides different conductance responses. What we think happens is that the magnetoconductance tells us about the density of the polarization states at both sides of the contact in a region smaller than the mean free path of the electron for spin reversal that is determined by the magnetic domain wall width at the contact. Then in the parallel spin configuration the electron can travel across the contact (low resistance state) but this is not so easy in the antiparallel configuration (high resistance) because there is strong backscattering for electrons with antiparallel spins. The reason that for small contacts the MR effect is larger may be explained basically if the domain wall increases with the size of the contact, but, perhaps also, because for larger contacts it is more difficult

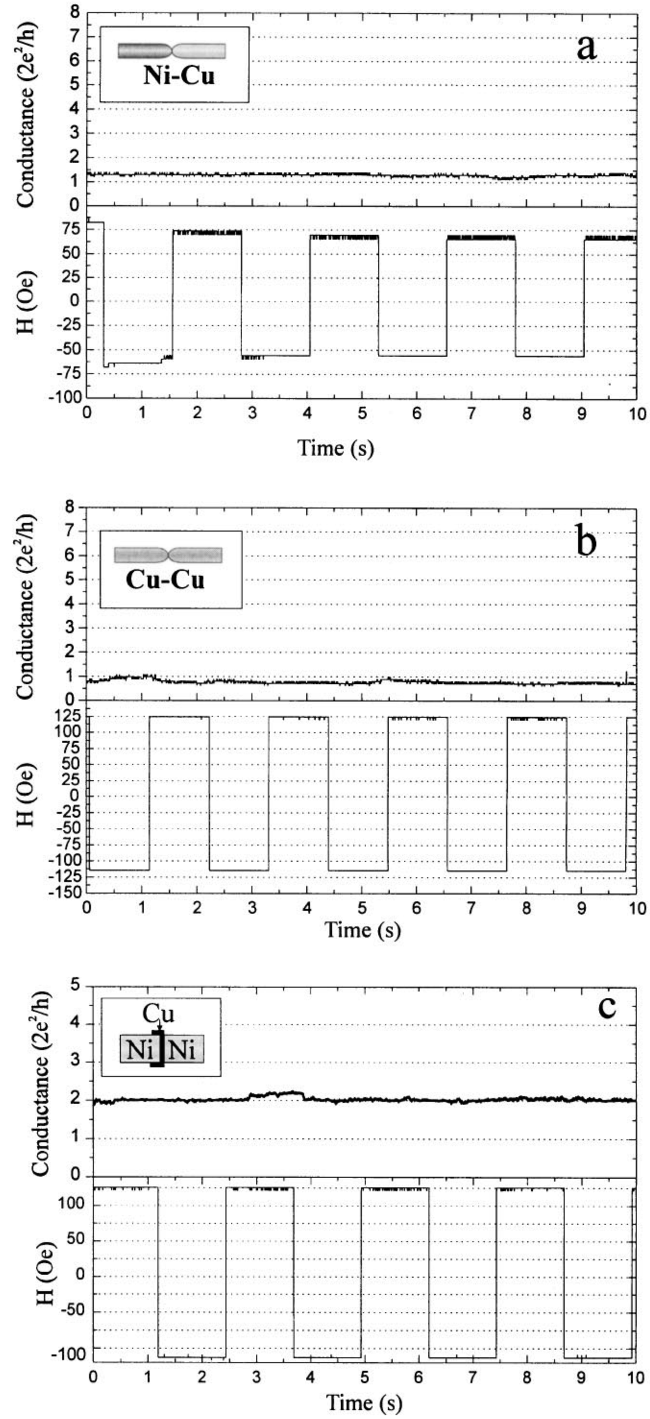

FIG. 3. Measurements on nanoconstrictions of different materials. (a) Ni-Cu nanoconstriction (15 samples, no effect); (b) Cu-Cu nanconstriction (50 samples, no effect); (c) a thin copper wire of 0.1 mm diameter is inserted in between the two nickel wires, thus the nanoconstriction is Ni-Cu and no magnetoresistive effect is observed (12 samples, no effect).

to reverse all the spins at the contact by the applied field. In this context, to explain the magnitude of the MR one should consider the possibility that the magnetic moment and consequently the density of states at the

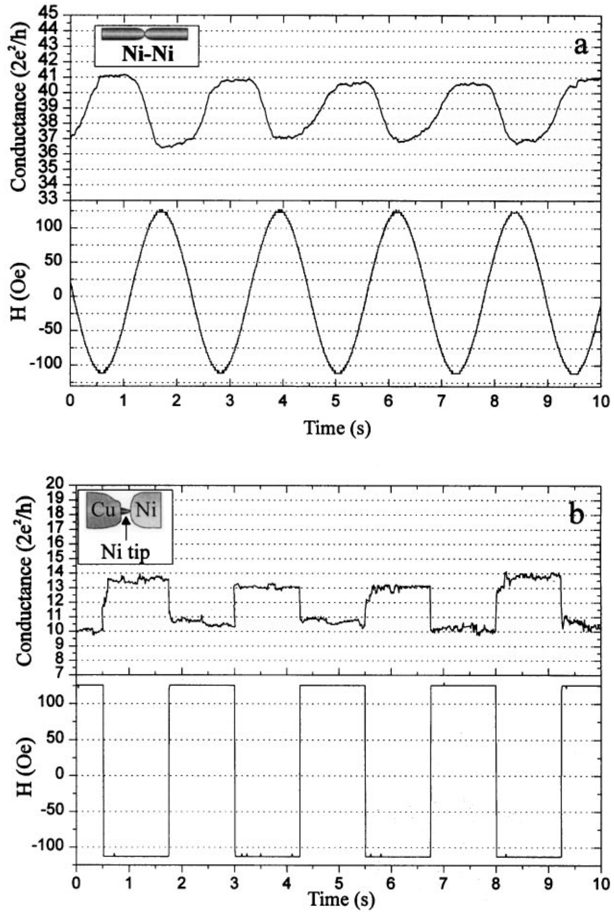

FIG. 4. Measurements on Ni-Ni nanoconstrictions under different conditions. (a) A sinusoid field is used to trigger the magnetoresistance (25 samples, effect); (b) one nickel wire is replaced by a copper wire ending with a small nickel tip (0.5 mm length), thus the nanoconstriction is still composed of Ni-Ni (10 samples, effect). In these experiments the field is in antiphase to see the appropiate behavior.

contact may differ from that of the bulk Ni. For example, calculations on Ni clusters find polarization of 1.6 Bohr magnetons for small Ni clusters [18] while the bulk Ni has 0.54 Bohr magnetons. In this way our experiments are able to provide information on the polarization state of minute-nanoscopic amounts of material and should be very good for detecting the magnetic response of materials.

In conclusion, we have presented room-temperature data showing very large magnetoresistance values in magnetic nanoconstrictions by the application of magnetic fields no higher than 120 Oe. This may open intriguing opportunities for a new generation of magnetoresistive devices.

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[17] Magnetostatic forces can also exist because the two magnetic wires are two magnets that can be attracted to or repelled from each other depending on the signs of M_1 and M_2. The magnetic forces are the same in the cases of Figs. 2a and 3c because this is equivalent to a force of a plane condenser (magnetic poles), and in both cases the force is the same if the size of the plates (diameter of the electrodes) is much larger than the separation between them as is the case; notice that the diameter of the Cu wire is 0.1 mm much smaller than the diameter of the wires (2 mm). For Fig. 4b the magnetostatic force arises from the interaction between a plane of poles (Ni electrode) and a small dipole corresponding to the small Ni tip deposited on the Cu wire. In as much as the field created by the plane of poles is constant the force acting on the dipole near the plane will be zero in first approximation.
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