# Negative and Positive Magnetoresistance Manipulation in an Electrodeposited Nanometer Ni Contact

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We show that, in a nanometric size stable electrodeposited Ni contact, it is possible to modify the magnetoresistance by applying current pulses and external magnetic fields whereby the same current path is used for detection and modification. We can pass from positive to negative magnetoresistance with values as large as 25% at room temperature, all in the same contact. We propose that the effect may be due to switching and moving domain walls in the contact region under the combination of current effects and external fields.

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One of the important issues in future nanotechnology development is spin dependent electronic devices. In particular, magnetoresistance (MR) is a basic signal for these devices. The giant magnetoresistance effect has been intensively studied in different systems [1–3]. Recently, we have reported [4] that very large ballistic magnetoresistance (BMR) can be realized in nanocontacts of ferromagnets such as Ni and Co. Through comprehensive studies [4] on the MR behavior in nanocontacts of different materials, it is shown that the BMR is a highly local effect which closely correlates to the local magnetization configuration in the nanocontact region [5].

In this paper, we report that at room temperature (RT) both positive and negative MR can exist in a single electrodeposited Ni nanoscopic stable contact between two macroscopic electrodes; the sign seems to be determined by the magnetization configurations near the contact and may be switched by pulsed current above a critical value. This opens interesting prospects for magnetic random access memories, since the same current path can be used for writing and reading. Moreover, the magnetoresistive behavior could be interpreted as a signature of the domain wall sweeping across the contact region.

The nanoscopic Ni contacts between two macroscopic electrode wires are electrochemically deposited from a saturated $NiSO_4$ aqueous solution at low *p*H value of $\sim 1-2$ and RT and their development should be important in magnetoelectronic device integration [6]. With the procedure described in [6], the resistance of the deposited contact is usually in the range of 1 to 500 $\Omega$, corresponding to cross sectional areas from tens to thousands of $nm^2$ (3–100 nm in diameter). Immediately after the electrodeposition, the resistance measurements usually show drifting up or down during a wide time range of 10 min to 2 h depending on individual sample, which is presumably associated with electromigration or slow relaxation of strains accumulated in the contact during the electrochemical process. This yields the very stable nanocontacts, over days, necessary for performing the following experiments on magnetic field cycling and current pulse effects.

Samples with geometry schematically shown in the inset of Fig. 1(b) are used: two polycrystalline nickel wires of 125 $\mu$m diameter and 5 mm length are arranged perpendicular to each other, and the nanoscopic contact is grown

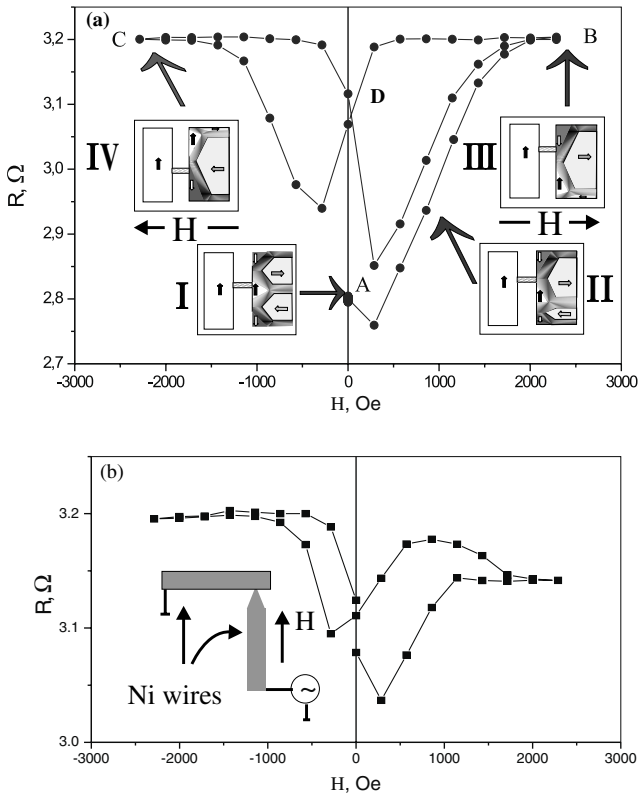


FIG. 1. (a) First $R(H)$ loops with the field parallel to one electrode and perpendicular to another; the insets illustrate the proposed model. (b) MR when the field is tilted about 30° with respect to the plane of the two electrodes but the in-plane component is still parallel to one electrode axis and perpendicular to another as in the first loop. Notice that in the negative field range the saturation resistance of (a) and (b) repeat exactly. The inset shows sample geometry. Notice that, for better visualization, the wire has been drawn longer than wide. In reality the wire for this case is about 10 times shorter than wide.

  

from the tip of the vertical wire towards the horizontal one. The sample is placed into a magnet system (Model M-50, MMR Technologies, Inc.) which can produce a homogeneous field up to 4.5 kOe. In order to investigate the high-density current dependence of the sample resistance and magnetoresistance, 100 ns current pulses with different amplitudes are applied to the contact at either zero field or a certain value of field. This permits one to combine applied field and injected current to manipulate MR.

In Fig. 1, we present two measurements showing resistance versus applied field [$R(H)$] loops up to $\pm 2.3$ kOe for a sample with 2.8 $\Omega$ initial resistance whose diameter is estimated to be about 30 nm and the length is much shorter ($1 \sim 2$ nm) by taking into account both ballistic and diffusive resistance. Figure 1(a) shows the first loop where the field is applied parallel to the vertical wire axis and perpendicular to the horizontal one; Fig. 1(b) is the second loop where the field direction is tilted about 30° with respect to the plane of the two electrodes but the in-plane component is still parallel to the vertical wire axis and perpendicular to the horizontal one. It is seen from the first loop (Fig. 1a) that, with increasing the field in the positive direction, the resistance first decreases slightly and then increases with field until it reaches a saturation value (3.20 $\Omega$) at about 2 kOe field which represents $\sim$14% MR defined as MR $= \frac{R(H)-R(0)}{R(0)} \times 100\%$, where $R(H)$ and $R(0)$ are the resistance under field $H$ and at zero field, respectively. It is interesting to note that the resistance maintains at the saturation value when the magnetic fields are swept down until about 570 Oe and then drops to the value of a remanent state. This is strong evidence that the involved domain wall (DW) is pinned by defects. Similar behavior is observed in the negative field direction. The second loop shown in Fig. 1(b) resembles to a great degree the first one, particularly in the negative field range, the saturation resistance repeats exactly. The magnetoresistance is positive in the present configuration of electrochemically grown nanocontacts.

Figures 2 and 3, present the influence of current pulses on the MR at zero field and an applied field of $-2.3$ kOe, respectively. Figure 2(a) shows the measured contact resistance versus time on applying pulses. The sample is first brought into the remanent state by sweeping through the $R(H)$ loops from state $A$ to state $D$ (dotted line with solid squares in Fig. 2b). From 415 to 1145 s, seven current pulses from 10 to 70 mA have been applied to the contact at 100 s intervals but no obvious change in resistance has been observed. Afterwards, however, each 100 ns current pulse of 80, 90, and 100 mA gives rise to a steplike drop in resistance. The total drop from point $D$ to the new configuration $E$ is about 18%. Thus, a critical current value must be exceeded in order to have influence on the resistance, which appears to be 80 mA for this particular contact, corresponding to a current density of $\sim 5 \times 10^9$ A/cm$^2$. After the current pulses, field sweeping (open triangles) can bring the changed magnetization configuration $E$ back to

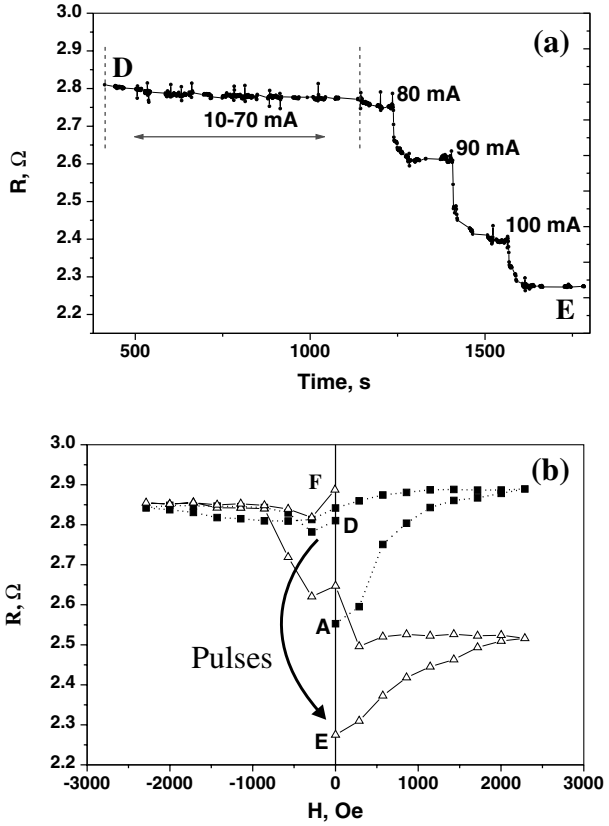


FIG. 2. (a) Influence of pulsed current on the resistance at zero field: during the time range marked by the two dotted vertical bars, seven current pulses of 10 to 70 mA are applied but the resistance is not influenced. The values of following current pulses are indicated on the figure; 80 mA is the critical current for this particular contact; (b) $R(H)$ loops before current pulses (dotted line with solid squares, start from $A$ and end with $D$) and after them (solid line with open triangles, from $E$ to $F$). The resistance change due to the current pulses is indicated by the bent arrow.

a state $F$, similar to the state $D$ before current pulses. This demonstrates that the resistance change by the pulsed current is a magnetoresistive effect rather than other spurious effects. We should mention that after current pulses sometimes several magnetic field sweeps are needed to reach the saturation in the MR. Analogous results, not shown here, are obtained for a sample with $R \sim 600$ $\Omega$.

Figure 3(a) shows the effect of a single current pulse of 100 mA in an applied field. The line with solid upward triangles shows the $R(H)$ sweep before current pulse. The current pulse was applied at $H = -2.3$ kOe, which causes a resistance drop ($\sim$24% MR) indicated by the thick arrow in Fig. 3(a). The effect of pulsed current thus dominates over the external magnetic field effect. The current pulse at positive applied field gives a similar result. The $R(H)$ loop after pulse is presented by the line with open diamonds in Fig. 3(a). It is important to note that after a pulse the MR does not approach the same saturation MR as before the pulse, in contrast to the data presented in Fig. 2; the

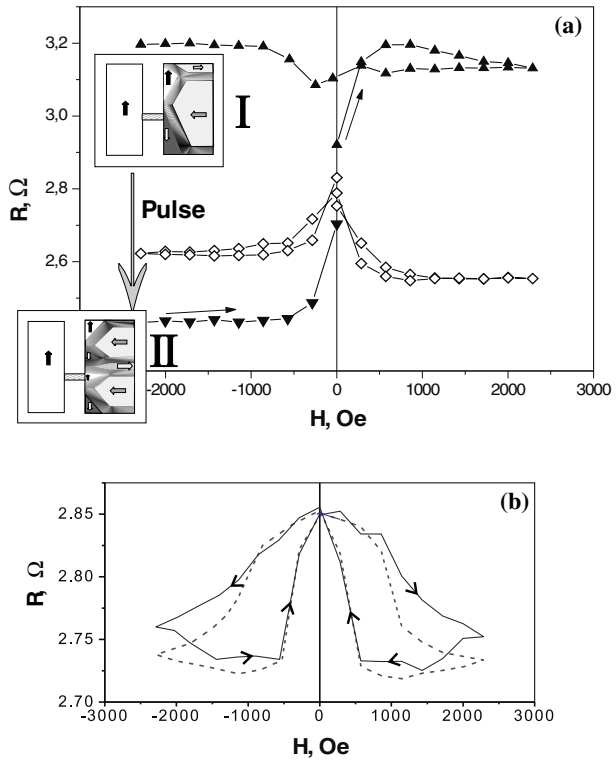


FIG. 3. (a) $R(H)$ measurements before and after current pulse at applied field of $-2.3$ kOe. The effect of the pulsed current on the resistance dominates over that by the applied field. The insets show the magnetization configuration at different stages. Notice that the $R(H)$ behavior after current pulse is different from that before current pulse, now a negative MR is observed. (b) $R(H)$ loops demonstrate reproducible negative MR after the current pulse at field of $-2.3$ kOe.

domain configuration, therefore, has been drastically restructured. A negative MR is observed now. Several $R(H)$ loops corresponding to this sample state are presented in Fig. 3(b) and exhibit reproducible negative magnetoresistance more than 5% at RT.

By analogy with the BMR picture [4], we suppose that the resistance of the investigated nanometric Ni contact is also determined by the configuration of local magnetization at both sides of the contact. Parallel magnetization corresponds to the low resistance and antiparallel to the high resistance. Also, the domain wall separating both electrodes is expected to be confined in the length of the contact ($\sim$1 nm) as was proposed in Ref. [4] and has been calculated recently [7]. This is very important because the short length interfacial DW produces strong scattering and gives rise to a large MR value. To describe the main experimental features, we propose a plausible model schematically shown in the series insets of Figs. 1(a) and 3(a), which are self-illustrating. Because of the sample geometry the easy-magnetic axes of the macroscopic wires are orthogonal to each other. Therefore, we assume the magnetization at the left side of the contact is determined mainly by shape anisotropy, points mainly along the wire axis although some local deviations due to the surface structures are possible, and remains unaffected when the field is applied perpendicular to its axis. This assumption holds, in general, as long as the applied field is smaller than the demagnetization field $4\pi M \approx 6000$ Oe for nickel. However, it is well known that the surface domain arrangement in a ferromagnet of cubic symmetry such as nickel is primarily determined by the principle of flux closure; we can reasonably expect the existence of closure domain structures at the top of a macroscopic wire [5,8]. This closure domain structure is schematically presented in the insets for the electrode at the right side of the contact—regions with different magnetization orientation (arrows in the insets show magnetization directions) are represented by the different scale of gray. Minimal size of the surface domain is of the order of the bulk domain wall, $\sim$60–150 nm [5]. Therefore the regions with a transition scale of gray in the insets correspond to the domain walls with rotation of magnetization.

Let us start from the initial configuration as shown in inset I of Fig. 1(a). It is reasonable to assume that the two adjacent regions of the contact prefer to have substantial parallel components corresponding to a low resistance state [point $A$ of Fig. 1(a)]. When a field is swept up in the positive direction, as illustrated in inset II of Fig. 1(a), a domain with magnetization parallel to the field expands thus eating the domain directly linked to the contact or shifting it away from the contact; i.e., a DW with thickness $\sim$60–150 nm is continuously moving through the contact. This process results in the continuous change of resistance with increasing field [trace $AB$ in Fig. 1(a)] since the magnetization vector within the wall changes continuously. The saturation resistance we associate with a predominantly antimagnetic state [inset III and point $B$ of Fig. 1(a)]. When the field is swept down, the resistance remains at the nearly saturation value, which is quite understandable if the DW near the contact is pinned by defects and grain boundaries. The process in the negative field direction can be similarly analyzed.

Although the data presented are up to fields of 2.3 kOe, the experiments have been done up to fields of 4.5 kOe; however, no variation in MR is observed between 2.3 and 4.5 kOe. This implies that the MR saturation corresponds approximately to the magnetization saturation. Furthermore, we have also measured Ni-Cu contacts and the MR $<0.5\%$; therefore the magnetostrictive effects can be ruled out.

There are two mechanisms which can describe the influence of a high current pulse on the magnetization near the contact. The first one is due to exchange driven excitations in the magnetization with emission of spin waves by the high density current [9–11] and another one is the rotational magnetic field induced by the current [12]. Experimentally observed switching of the MR by current has been attributed to exchange driven excitation [13,14]. It was theoretically shown and experimentally observed in the Ni-Fe films [9,12] that both of the two effects can

lead to current-induced displacement of the domain walls. The rotational magnetic field induced by the current pulses can be very large, for a current of 80 mA and the contact of 30 nm diameter, $H \sim 10$ kOe, and the field gradient $\sim 5 \times 10^{11}$ Oe/m, i.e., an order of magnitude larger than those which stabilize domain walls. This field is larger than the applied field and localized in the contact region which makes it more effective to release the pinned DWs in the vicinity of the contact and further push the DWs away from the contact [5,12] that may lead to the resistance jumps.

We, therefore, tend to believe that the current-induced local magnetic fields together with the applied uniform field are mainly responsible for the experimentally observed features although a contribution due to exchange driven excitations cannot be excluded. The antiferromagnetic state presented in insets III and IV of Fig. 1a corresponds to the existing very sharp domain wall between macroscopic Ni wires. Remanent MR (see Fig. 1a, point *D*) corresponds to a remanent, nonequilibrium magnetization of the system. The circular magnetic field induced by current transforms the domain structures near the contact to a new state *E*, with considerably lower resistance than the initial state *A*. Since the circular fields on each side of the contact are parallel, it is reasonable to assume that they favor parallel alignment, which leads to a state *E* exhibiting more parallel alignment than the initial state *A* and which cannot be reached by field sweepings alone.

With the current pulse applied in the presence of a uniform field, one arrives likewise at a state of lower resistance than the initial zero field state. On removing the applied field, however, the resistance increases, and consecutive field sweeping does not recover the initial $R(H)$ sweeps, but instead the magnetoresistance stays negative. The fact that the initial state can no longer be reached by uniform field cycles might indicate that the skewed fields due to circular fields and applied field changed also the magnetic configuration on the left side of the contact.

Finally, we have sketched a domain distribution for an idealized system that may be speculative in our polycrystalline wires. However, this paper does not deal with domain wall structure determination and knowing the domain wall structure is not necessary for understanding the physics of our experiments, because whenever magnetization changes in the contact region, a DW sweeps over the contact [4,6], there is a change in the MR. This is one of the main points of our results: we just need a local change of magnetization at the contact region, no matter what the global magnetization and the domain structure.

In summary, we have shown that the same nanocontact can exhibit negative and positive MR that can account for up to 25% at RT and 300 Oe applied external fields. The magnetoresistive behavior is interpreted to be a signature of the domain wall sweeping across the contact region. The switching from positive to negative MR is performed by applying a current pulse in an external magnetic field. The facts that this can be done in the same contact and that the same current path can be used to induce a particular magnetic state in the presence or the absence of an external magnetic field and to detect it are expected to be important in magnetoelectronics applications [6].

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*Note added.*—We have recently obtained preliminary experimental results showing that in electrodeposited Ni nanocontacts with $\sim 10\ \Omega$ resistance the MR can be larger than 100% at RT and low applied field. This is now under intensive investigation.

[1] M. N. Baibich *et al.,* Phys. Rev. Lett. **61**, 2472 (1988); G. Binasch *et al.,* Phys. Rev. B **39**, 4828 (1989).
[2] A. E. Berkowitz *et al.,* Phys. Rev. Lett. **68**, 3745 (1992); J. Q. Xiao, J. S. Jiang, and C. L. Chien, Phys. Rev. Lett. **68**, 3749 (1992).
[3] V. S. Speriosu *et al.,* Phys. Rev. B **44**, 5358 (1991).
[4] N. García, M. Muñoz, and Y.-W. Zhao, Phys. Rev. Lett. **82**, 2923 (1999); G. Tatara, Y.-W. Zhao, M. Muñoz, and N. García, Phys. Rev. Lett. **83**, 2030 (1999); Y.-W. Zhao, M. Muñoz, G. Tatara, and N. García (unpublished).
[5] S. A. Minyukov and N. Garcia, J. Magn. Magn. Mater. **214**, 327 (2000).
[6] N. García, M. Muñoz, H. Rohrer, I. G. Saveliev, and Y.-W. Zhao, Spanish Patent No. P9902667, 1999; N. García, I. G. Saveliev, Y.-W. Zhao, and A. Zlatkine, J. Magn. Magn. Mater. **214**, 7 (2000).
[7] P. Bruno, Phys. Rev. Lett. **83**, 2425 (1999).
[8] A. Hubert and R. Schäfer, *Magnetic Domains* (Springer-Verlag, Berlin, 1998).
[9] L. Berger, Phys. Rev. B **54**, 9353 (1996); C.-Y. Hung and L. Berger, J. Appl. Phys. **63**, 4276 (1988).
[10] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996); J. C. Slonczewski, "Exchange Driven Magnetic Excitation and Integrated Magnetoelectronics," 1999 (to be published).
[11] Ya. B. Bazaliy, B. A. Jones, and S.-C. Zhang, Phys. Rev. B **57**, R3213 (1998).
[12] E. Salhi and L. Berger, J. Appl. Phys. **76**, 4787 (1994); K. Bussmann, G. A. Prinz, S.-F. Cheng, and D. Wang, Appl. Phys. Lett. **75**, 2476 (1999); C. H. Back *et al.,* Science **285**, 864 (1999).
[13] M. V. Tsoi *et al.,* Phys. Rev. Lett. **80**, 4281 (1998); E. B. Myers *et al.,* Science **285**, 867 (1999).
[14] J.-E. Wegrowe *et al.,* Europhys. Lett. **45**, 626 (1999).