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Ballistic magnetoresistance over 3000% in Ni nanocontacts at room temperature

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This paper reports ballistic magnetoresistance (BMR) measurements in Ni nanocontacts made by electrodeposition. BMR in excess of 3000% is observed at room temperature and the observed large values of BMR are obtained in switching fields of only a few hundred oersteds. The results are attributed to spin-dependent electron transport across nanometer sharp domain walls within the nanocontacts.

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The rapidly expanding field of magnetoelectronics is adding new facets of understanding to the known body of knowledge of physics of magnetism. Magnetoelectronic devices, both existing and envisioned, rely on spin-dependent transport of electrons. For example, the current read heads for high-density data storage devices are based on ''giant'' magnetoresistance or GMR effect—a spin-dependent effect discovered just over a decade ago.[1] Even higher sensitivity read heads are being investigated for future ultrahigh density storage systems (in terabits/in^2 range) having size comparable to the nanoscale bits. Ballistic magnetoresistance effect (BMR) in ferromagnetic nanocontacts is a promising avenue in this regard.[2] The BMR effect arises from nonadiabatic spin scattering across very narrow (atomic scale) magnetic domain walls trapped at nano-sized constrictions.[3–5] In the present study, we report the observation of a remarkably large room-temperature BMR effect in Ni nanocontacts. The observed BMR values we report are in excess of 3000% and are achieved at low switching fields (less than a few hundred oersteds). The observation of such high BMR values raises interesting fundamental questions regarding the nature of spin-dependent electron transport across narrow domain walls in nanocontacts. At the same time, high BMR at low switching fields offers exciting technological possibilities.

In the present study, the BMR measurements were made on Ni nanocontacts electrodeposited between Ni wires. The wires are arranged in a *T* configuration as shown in Fig. 1. The applied field during magnetoresistance measurements is in the directions of the Ni wire labeled I in Fig. 1. This arrangement, originally conceived by Garcia *et al.*,[6] is well suited for magnetoresistance measurements owing to different direction of shape-induced anisotropy in the two Ni wires across the Ni nanocontact. This is also the configuration in which Garcia *et al.*[6] had earlier reported a 400–700 % BMR effect at room temperature. The tip of the wire in Fig. 1 was positioned to within a few microns to few tens of microns of the Ni wire labeled II. Prior to electrodeposition of the Ni nanocontact, the Ni wires (except for the region in the immediate vicinity of the tip) were insulated by a fast curing resin epoxy in order to limit the deposition in the gap between the wires. The resin epoxy also firmly holds the Ni wires on the underlying glass substrate. The Ni nanocontacts were electrochemically deposited at room temperature. Electrodeposition was performed from a nickel sulfamate electrolyte (pH$=3.4$). We used a cathode potential of -1.1 V versus a saturated calomel electrode. Deposition times to establish a Ni nanocontact were typically less than 1 min; the columnar nature of the electrodeposited Ni is shown in the scanning electron micrograph in the inset in Fig. 1. The magnetoresistance was measured using the standard lock-in method at 200 μA constant current through the nanocontact and an applied field between ± 2.5 kOe. We experimented with different tip shapes for the Ni wire labeled I in Fig. 1. Tips were made by mechanically breaking the Ni wire as well as sharp tips (radius between 40 and 400 nm) using an electrochemical etching technique that is commonly used for making scanning tunneling microscopy tips.[7] The electrochemical technique to make the tips is shown in Figs. 2(a) and 2(b). Figure 2(a) shows a Pt cathode in the form of a ring, which holds a thin film of electrolyte (2.0 M KCl) suspended by surface tension. In Fig. 2(a), a vertical Ni wire (anode) passes through the electrolyte. When a constant voltage is applied to this electrochemical cell (typically 2.0–2.1 V), only a very narrow region of the Ni wire in contact with the electrolyte is etched according to the anodic reaction $\mathrm{Ni}(s)+2\mathrm{Cl}^- \rightarrow \mathrm{NiCl}_2+2e$; the reaction occurring at the Pt cathode is $2\mathrm{H}_2\mathrm{O}+2e \rightarrow \mathrm{H}_2(g)+2\mathrm{OH}^-$. As shown in Fig. 2(b), when the Ni wire was electrochemically cut, the lower portion of the Ni wire slid on the electrolyte film at which point the applied voltage was turned off. It was found that the bottom halves of the Ni wire had a longer taper [Fig. 2(c)] and a sharper tip ($\approx$40 nm) in comparison to the upper halves ($\approx$400 nm radius), Fig. 2(d). In addition, Fig. 2(e) shows the tip profile of a mechanically broken Ni wire,

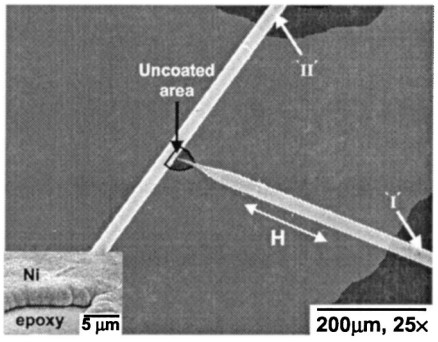

FIG. 1. Scanning electron micrograph of the 125-μm-diameter Ni wires in a *T* configuration. The electrodeposited Ni nanocontact is deposited in the gap between the tip of the Ni wire labeled I and the wire labeled II. The inset shows the columnar growth of the electrodeposited Ni.

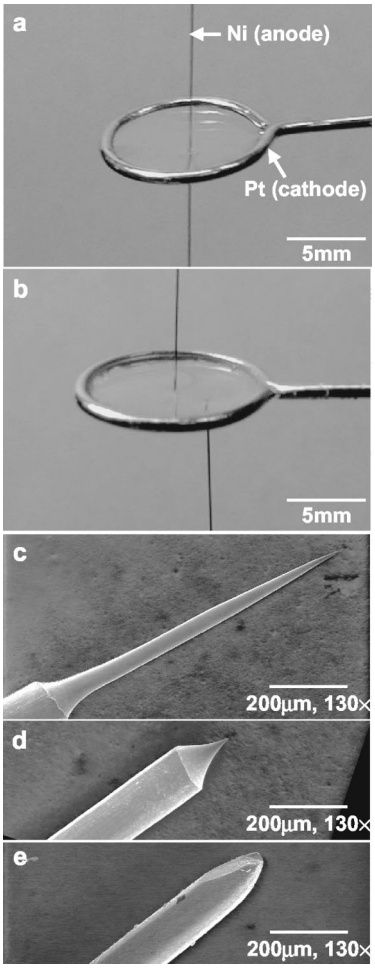

FIG. 2. Micrographs showing the electropolishing of the Ni wire to obtain sharp tips. (a) The anodic Ni wire shown passing through the cathode made of a Pt ring. The Pt ring holds the electrolyte by surface tension. (b) The lower Ni wire shown displaced slightly from the upper portion of the Ni wire after the Ni wire is cut electrolytically. (c), (d) Respective tip profiles of the bottom and top portions of the Ni tips obtained after electropolishing. (c) Profile of a mechanically broken Ni wire.

which is considerably less well defined than the electrochemically prepared tips. Nevertheless it consists of several sharp points across which a nanocontact can form during electrodeposition.

Figure 3 shows consecutive magnetoresistance loops in a sample whose initial zero-field contact resistance was 8 Ω after electrodeposition. This contact resistance R_c determines the diameter $d=\sqrt{1000/R_c(\Omega)}$ (in nm) of the nanocontact,[6] being equal to 11 nm for this sample (assuming a quantum resistance of 12.9 kΩ is associated with one single atom occupying an area of 0.1 nm^2).[6] As seen from Fig. 3, the resistance increases rapidly with increasing field strength. At saturation (in fields that are less than 500 Oe in Fig. 3), the resistance rises to ≈260 Ω, after which it remains essentially unchanged with further increase in field strength. This represents a remarkable 33-fold change in resistance, or ≈3150% BMR at room temperature, in fields less than ≈500 Oe, with the sample exhibiting a coercivity of ≈162 Oe. Also, in over

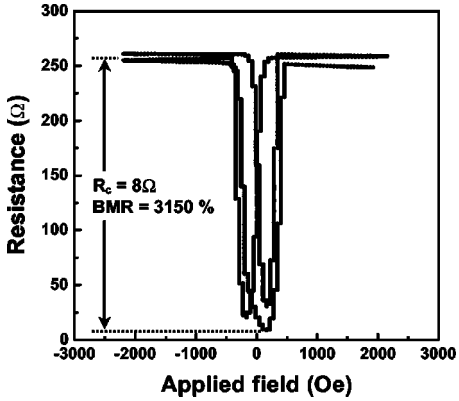

FIG. 3. Successive BMR loops from a Ni nanocontact showing 3150% BMR.

100 samples that were made for the present study, it was found that for contact resistance less than 4 Ω, the BMR rarely exceeded 500%, and in only one case a BMR of 515% was obtained in a 4 Ω contact resistance sample.

Figure 3 shows that during successive cycling of the sample within the applied range of field excursion, although the low-field resistance increases somewhat, the high-field saturation resistance remains virtually unchanged. This change in low-field resistance with each successive cycle was found to be very nearly reversible with time. For instance, the BMR loops measured within half an hour of the first measurement nearly recovered the initial contact resistance (to ≈10 Ω) and high BMR value approaching over 2600%, while the high-field saturation resistance remained essentially unchanged (270 Ω). As in previously reported studies,[6,8,9] it is difficult to directly obtain a series of samples that have exactly the same nanocontact geometry and domain-wall configuration within the confines of the nanocontact. This makes a meaningful relationship between contact resistance and BMR difficult. A large variation in BMR in different samples even with the same contact resistance is due to the fact that the BMR is not a function of the nanocontact diameter alone. The form of the wall at the nanocontact, giving rise to spin scattering, also depends on the geometrical form of the nanocontact.[10] In this regard, the constancy of the saturation resistance in Fig. 3 and over time in subsequent measurements on the *same* sample offers a means of inferring the relationship between BMR vs contact resistance of the nanocontact (which in the same sample is likely to result from a similar contact geometry and differing only in size), as shown in Fig. 4. As seen from Fig. 4, the BMR decreases with increase in R_c, dropping from 3150% for a contact resistance of 8 Ω to ≈636% for contact resistance of 36 Ω.

Finally, the ballistic magnetoresistance is a result of the spin-dependent scattering of electrons across the nanocontact from a ferromagnetic aligned state (low resistance state) to an antiferromagnetic aligned state (high resistance) in an applied field. One plausible domain configuration giving rise to a ferromagnetic aligned state at low applied fields and an antiferromagnetic aligned state at high fields in Ni samples with *T* configuration is given by Garcia *et al.*[11] In bulk ferromagnets, Cabrera and Falicov[3] and later Tartara and

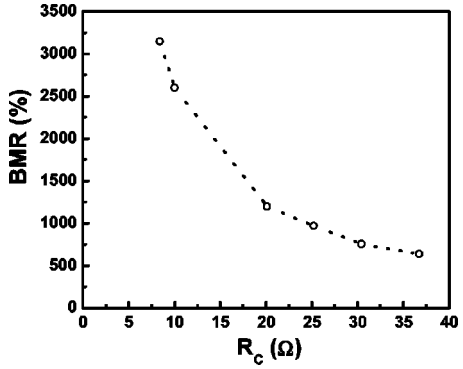

FIG. 4. Variation in BMR as a function of contact radius, as inferred from change in low-field resistance over successive cycles in Fig. 3 and several other measurements taken from the same sample.

Fukuyama[4] have shown that the spin-dependent scattering by domain walls is negligible, owing to the adiabatic nature of electron transport across a wall which is typically of the order of several tens of nanometers wide. Unlike in bulk ferromagnets (or thin films) Bruno has recently shown that atomically sharp domain walls can form in point contacts,[10] giving rise to the nonadiabatic nature of spin scattering and a very large BMR at room temperature. Various energetically possible, atomically sharp walls (Néel type, Bloch type, or vortex walls) and mode fluctuations between them have recently been discussed by Coey, Berger, and Labaye.[12] Their analysis also shows that mode fluctuations can give a variation in the magnitude of BMR. The form(s) and the width of the domain wall at the nanocontact (and the dependence of BMR on these factors) depend on the geometry of the nanocontact itself and remain to be investigated. The existing theory to predict the magnitude of BMR (Ref. 5) cannot explain the very high BMR effect in this study as well as the observation of previously reported[6] high values of up to 700%. While the spin-dependent scattering, nature of domains walls, and geometry of nanocontact play a key role in the observed high BMR effect, their exact role remains as yet unexplored; an exact formulation of spin-dependent scattering on the above factors is not within the scope of the present paper. The present results are likely to raise interesting fundamental questions. At the same time, the observation of such a high magnetoresistance effect at low fields is exciting from the viewpoint of technological applications.

Note added in Proof. Spin splitting of quantized conduction states offers a plausible mechanism for the observed large BMR effect; see also recent theoretical article by Tagirov *et al.*[13] and Ref. 17 within it. If the quantized conduction states are spin split, then only electrons of one spin can go through the constriction in the ferromagnetically aligned states, i.e., a finite resistance state. In the antiferromagnetic aligned state in the presence of a domain wall inside the nanocontact, the electron would be required to have one spin at one end of the nanocontact and the other spin at the other end. The nanometer length scale of the nanocontact does not give enough time for electrons to adjust to the rapidly changing magnetization profile, and none can get through, i.e., infinite resistance state.[13,14] Spin flip and nonideal contacts would lead to a very large instead of finite resistance.

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