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100,000 % ballistic magnetoresistance in stable Ni nanocontacts at room temperature

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This study reports reproducible, ten thousand to hundred thousand percent ballistic magnetoresistance (BMR) effect in stable electrodeposited Ni nanocontacts at room temperature and in fields of only a few hundred oersteds. Experimental observation of Ni whiskers and nanoconstrictions within these whiskers formed during electrodeposition points towards a picture of multiple ballistic, quasi-ballistic, and diffusive conductors acting in series and parallel to give rise to the observed large BMR effect, instead of a single, monolithic nanocontact.

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Spintronics devices rely on the spin splitting of electrons in ferromagnetic materials during transport, and are currently the focus of intense research activity. For example, read heads are currently being investigated for future ultra-high-density storage systems (in the terabits/in^2 range) having size comparable to the nanoscale bits. Ballistic magnetoresistance (BMR) in ferromagnetic nanocontacts is a promising avenue in this regard.[1–3] Recently, the authors reported a remarkably large BMR effect ≈3150% in electrodeposited Ni nanocontacts at room temperature and in fields of only a few hundred oersteds.[4] In the present study, a simple and elegant self-terminating electrodeposition method due to Boussaad and Tao[5] has been used to make stable and reproducible Ni nanocontacts. Such samples routinely exhibit several thousand percent BMR. Due to space limitation, detailed experimental results will be discussed elsewhere,[6] which rules out magnetostriction effects and show a sensitive dependence of BMR on solution chemistry, *p*H, and deposition conditions.

The experimental details to make Ni nanocontacts are the same as in a previous report,[4] *with one main exception*. In the previous study,[4] nanocontacts were deposited on electropolished Ni tips. In the present study, samples were made using *only* mechanically pulled Ni wires to eliminate the possibility of any extraneous chemical layer being present. Nanocontacts so made gave more stable nanocontacts than previously reported,[4] and, also significantly, are much easier to make. The standard three-electrode setup was employed to make the nanocontacts. In the three-electrode system, in addition to the test electrode and the reference electrode, an auxiliary electrode is added. In Fig. 1, the test electrode is the Ni wire labeled ''II,'' whereas the Ni wire labeled ''I'' is the auxiliary electrode. For the setup shown in Fig. 1, the current flows *only* between the test electrode and the auxiliary electrode. A high impedance voltmeter is placed between the test electrode and the reference electrode to prevent any significant current from flowing between them. In this manner, the potential of the test electrode can be accurately monitored with respect to the reference electrode.

In the present study, Boussaad and Tao's self-terminating electro-deposition technique was used to make nanocontacts, details of which are given elsewhere.[5] Briefly, the experimental layout of the self-terminating electrochemical method is the same as in Fig. 1, except that an external resistor R_{ext} (less than the quantum resistance of 12.9 kΩ, and typically 500–2000 Ω in the present study) is connected in series with the test electrode. As soon as the contact is formed between the two wires, the applied voltage across the electrodes drops and gets established across R_{ext}. As a result the growth of the nanocontact *slows considerably*, at which point the electrodeposition is stopped.

Note that the self-termination method works *precisely* in relatively dilute electrolytes as it is based on diffusion-controlled ion transport, whereas a concentrated electrolyte was used in the present study. The BMR loops were measured using both the direct current and the standard lock-in ac method at 1–300-μA constant current and an applied field up to ±3.0 kOe.

Figure 2(a) shows consecutive BMR loops in a sample whose initial zero-field contact resistance was 6 Ω after electrodeposition. As seen from Fig. 2(a), the resistance increases

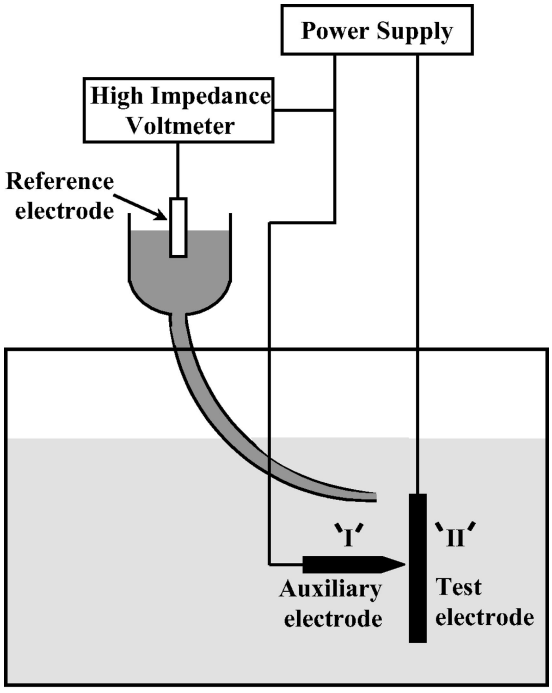

FIG. 1. Experimental layout of the electrodeposition method using the three-electrode system.

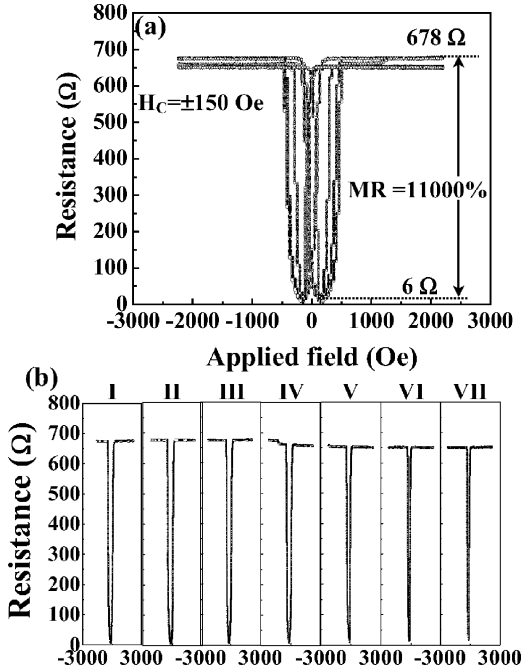

FIG. 2. (a) Seven successive positive BMR loops measured from a sample, which shows a 11 000% effect. Each of the seven loops shown in (a) are shown separately in panels I through VII in (b) to emphasize the stable nature of the nanocontact.

rapidly with increasing field strength. At saturation the resistance rises sharply to ≈678 Ω, after which it remains unchanged with further increase in field strength. This represents a remarkable 113-fold change in resistance, or ≈11 000% BMR at room temperature, in fields less than ≈500 Oe. Also note that the sample exhibits a well-defined coercivity of ±150 Oe. Figure 2(b) shows the same BMR loops in Fig. 2(a), but each loop is now shown individually in separate panels, labeled I through VII, in order to highlight the remarkable stability of the nanocontact over repeated measurements. The direction of the applied field for each loop (+3000 to −3000 Oe or −3000 Oe to +3000 Oe) is also indicated along the horizontal axis in each panel in Fig. 2(b). Note the highly stable nature of the loops, from the saturation resistance values for successive cycles: cycle I: 654.2 Ω, cycle II: 654.2 Ω; cycle III: 653.0 Ω; cycle IV: 653.0/651.8 Ω; and for cycles V–VII: 651.8. From Fig. 2(b), also note that the low field resistance is ≈6–7 Ω for loops I through V, and then it increases to 15 Ω for loops VI and VII.

As in the previous study,[4] samples were found to exhibit either positive or negative BMR loops. Figure 3 show seven consecutive loops in a sample, which shows negative BMR. In Fig. 3, the sample exhibits a maximum BMR of 3700% (corresponding to a resistance change from 761 Ω peak value to 20 Ω at high fields), as well as a well-defined coercivity of ±300 Oe. Individual loops showed that the BMR is 1575% in the first cycle, 3100% and 3700% in cycles II and III, respectively, and stabilizes to ≈2200% in the remaining cycles. In other words, the BMR does not decay after the first loop to lower values.

Whereas Figs. 2 and 3 show a high BMR of several thousand percent, Figs 4(a) and 4(b) show, respectively, an even

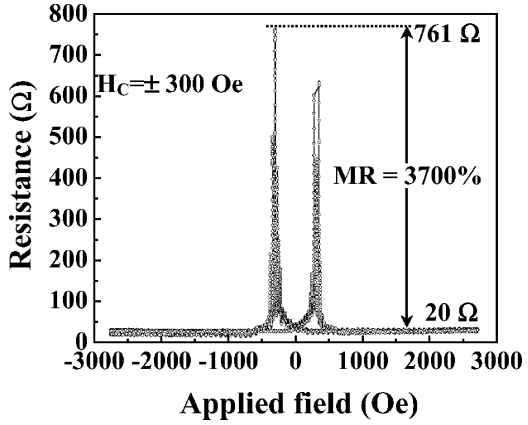

FIG. 3. Seven successive BMR loops measured from a sample, which shows a maximum negative BMR of 3700%.

more remarkably high BMR effect approaching 70 000% to 100 000% in two different samples. (Several other samples with very high values, ranging from 30 000% to 100 000% BMR were also measured). In Figs. 4(a) and 4(b), each loop has been plotted separately to emphasize the stable nature of the effect over several cycles. In particular, these two samples were continuously cycled for over an hour without observing any noticeable degradation of the effect. The sample in Fig. 4(a) changes its resistance from ≈1 Ω at low fields to ≈830–850 Ω at high fields (more precisely from 1.2

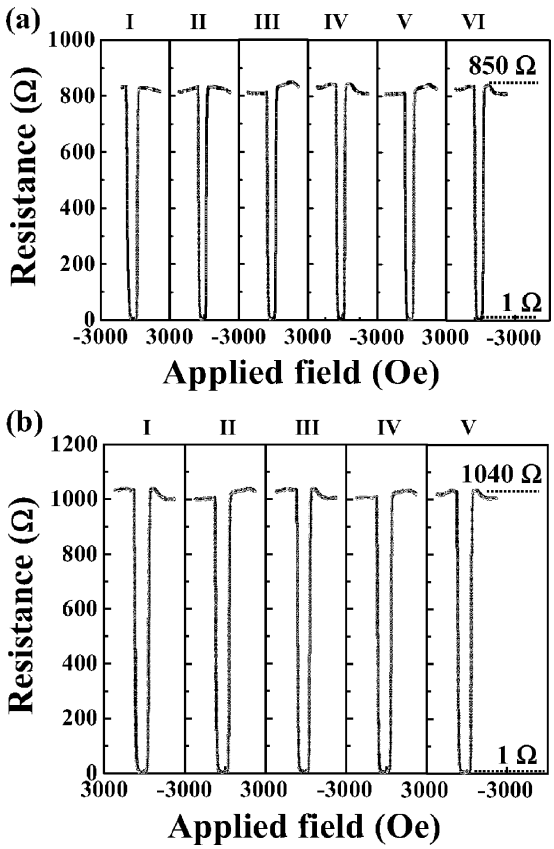

FIG. 4. (a) and (b) Seven successive BMR loops from two different samples, approaching 70 000% to 100 000%, respectively.

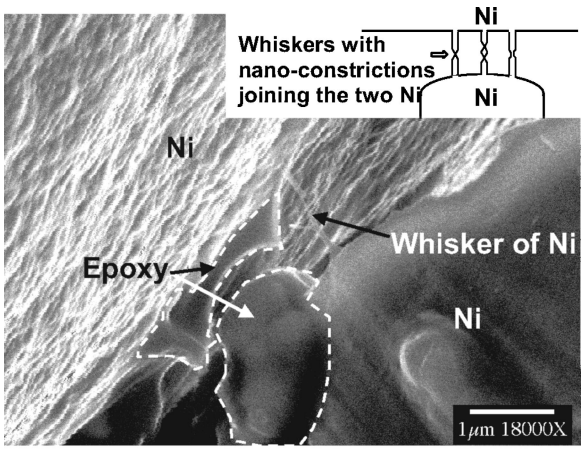

FIG. 5. Scanning electron micrograph showing a Ni nanowhisker between the Ni wires. The image was recorded using backscattered electrons, which established the composition of the (Ni) whisker. The inset shows a schematic of nanowhiskers with nanoconstrictions, depicting multiple conductors across the two Ni wires in series and in parallel.

Ω to $\approx$830–850 Ω). This represents a 708-fold change in resistance or a $\approx$70 000% BMR effect. The sample in Fig. 4(b) shows an even higher BMR effect with resistance changing from $\approx$1 Ω at low fields to $\approx$1040 Ω at high fields, representing a BMR of the order of 100 000%.

Ordinary diffusive transport cannot adequately explain either the sign or the magnitude of the large BMR effect. At first sight, ballistic transport also appears unlikely since the *apparent* resistance of the loops at low fields (in positive BMR samples) is of the order of a few ohms (corresponding to a contact diameter of a few nm to few tens of nm, and being too large for true ballistic transport). This is an *apparent* quandary. However, note that during deposition formation of more than one nanocontact is probable due to the irregular electrodeposition at tip asperities, especially when the deposited Ni narrows the gap between the wires. The present study has succeeded in visually observing the morphology of the Ni nanocontact using scanning electron microscopy (SEM) and backscattered SEM (for composition analysis). SEM results show that the final contact between the two Ni wires is made in the form of Ni whiskers, as shown in the SEM micrograph in Fig. 5; backscattered imaging confirmed the whisker in Fig. 5 as being composed of Ni. The upper and lower stems of the whisker in Fig. 5 are ten to several tens of nm thick, respectively. However, the midportion of the whisker was found to be extremely narrow to be adequately resolved even with a field emission gun SEM. This observation points toward a picture of several diffusive, quasiballistic, and/or ballistic nanocontacts acting in series and parallel, as shown schematically in the inset in Fig. 5, to give rise to the observed BMR effect. In this regard, also note that the analysis of quantized conductors in parallel and series do not follow a simple Ohm's law, and their transmission characteristics in the presence of magnetic domain walls would have to be investigated. It is also intriguing to note that the large saturation resistance values of 700–1000 Ω in Figs. 2 and 4 are equivalent to only a few conductance channels, *if that were to be the case*. The existing literature also shows experimentally[7–9] that ballistic nanocontacts in series can give rise to a net resistance that can be considerably lower than the sum of each resistor. A theoretical framework to explain this effect also exists.[10,11] These experiments were conducted in nonmagnetic nanocontacts. It remains to be investigated whether such an effect can give rise to a significantly enhanced forward transmission in positive BMR loops in metals where the Fermi wavelength is much smaller than in semiconductor two-dimensional electron gas, but where a single nanoconstriction could host multiple ballistic conductors. An alternative possibility is the formation of a thin super-antiferromagnetic NiO layer at the nanocontact.

Finally, a note on parasitic effects arising from magnetostriction is warranted. A simple calculation shows that the fractional change in the resistance due to dimensional changes associated with magnetostriction is only of the order of 0.005% (assuming a Poisson ratio of 0.3). Another possibility is the breaking and rejoining of the Ni whiskers. This possibility can also be easily ruled out, because once a contact is broken it would give a resistance at least greater than 12.9 kΩ or discontinuous jumps in the BMR loops (let alone reproducibility as in the present study). Also note that 5000 data points were recorded per second, and each cycle (from, say, positive to negative fields) takes between 10 and 15 sec. In other words there are 50 000–75 000 data points in one loop, which showed no discontinuous jumps. The local necking of the nanocontacts would also lead to irreversibility for any localized straining beyond a 0.2% offset strain. Detailed experimental results discussed elsewhere[6] show a large BMR effect in Ni-coated Cu wires, where magnetostriction can be ruled out. In addition, Cu nanocontacts over a large range of contact diameters between Ni wires also show no MR-like effect, thereby ruling out any magnetomechanical motion associated with (already constrained) Ni wires on to the substrates. Also see Refs. 2 and 12, that describe other experiments, which also eliminates magnetostriction as the cause of the large BMR effect.

In conclusion, BMR values in excess of 70 000–100 000% have been observed in electrodeposited Ni nanocontacts. An experimental observation of Ni whiskers with nanoconstrictions formed during electrodeposition points toward a picture of several ballistic, quasiballistic, and diffusive conductors acting in parallel and series to give rise to the observed large effect, instead of the previously assumed single, monolithic nanocontact.

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