Magnetoresistance of nickel nanocontacts fabricated by different methods

H.-X. Wei and T.-X. Wang

State Key Laboratory of Magnetism, Institute of Physics, Chinese Academy of Sciences,
Beijing 100080, China

E. Clifford and R. M. Langford

Physics Department and CRANN, Trinity College, Dublin 2, Ireland

X.-F. Han

State Key Laboratory of Magnetism, Institute of Physics, Chinese Academy of Sciences,
Beijing 100080, China

J. M. D. Coey^{a)}

Physics Department and ORANN, Trinity College, Dublin 2, Ireland

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Nickel nanocontacts have been fabricated by focused ion-beam (FIB) milling of *e*-beam patterned planar contacts, FIB milling of conical-shaped nanoporations in a silicon nitride membrane, and nanoimprinting using an atomic force microscope. Their sizes ranged from 1 to 30 nm. Magnetoresistance of up to 3% is developed in a field of a few millitesla. This is interpreted in terms of ballistic magnetoresistance across a wide domain wall whose structure is determined by dipolar interactions at the contact. © 2006 American Institute of Physics. [DOI: [10.1063/1.2167061](https://doi.org/10.1063/1.2167061)]

Reports of large values of magnetoresistance in ferromagnetic nanocontacts have aroused considerable interest and controversy.^{1–5} García *et al.*⁴ described electrodeposited nanocontacts across nickel wires in a “T” geometry. Chopra and Hua¹ reported magnetoresistance of up to 100 000% for whiskers formed by electrodeposition onto nickel wires. Values of up to 100% (Refs. 6 and 7) have been reported for Ni nanocontacts fabricated by focused ion-beam (FIB) milling of *e*-beam lithographically defined patterns and values of 40% have been reported for Ni break junctions.⁸ Nonadiabatic spin scattering across a very narrow domain wall trapped at a nanocontact could account for ballistic magnetoresistance of up to 400%.⁹ Larger values might be associated with a magnetic dead layer at the nanocontact¹ or with the presence of spin polarized oxygen there.¹⁰

These reports are hotly debated¹¹ and there have also been numerous experiments where no significant magnetoresistance was observed. Egelhoff and co-workers^{12,13} re-examined the systems used in the work by Chopra and Hua² and García *et al.*^{1,3–5} and argued that the large magnetoresistance values were experimental artifacts due to contacts breaking under the influence of magnetostriction or magnetic dipole forces. Similar conclusions were drawn by Yang *et al.*¹⁴ who monitored nickel electrodeposition across *e*-beam lithographically and FIB-trimmed contacts and by Gabureac *et al.*¹⁵ who used suspended Ni break junctions. Although Yang *et al.* found quantized conductance within their nickel nanocontacts, they observed no magnetoresistance larger than 1%. Ozatay *et al.*¹⁶ reported similar values in perpendicular nickel nanocontacts fabricated in silicon nitride membranes using *e*-beam lithography and reactive ion etching. Other fabrication methods that have yielded insignificant magnetoresistance are *e*-beam lithography to prepare nano-

holes in a bilayer resist¹⁷ and low-energy ion milling¹⁸ to fabricate perpendicular Co nanocontacts and planar Co nanoconstrictions. In stable nanoconstrictions magnetoresistance is not larger than 1%.¹⁷

We have fabricated nickel nanocontacts by three different methods to see if any large magnetoresistance effect can be reproduced. Planar contacts were made by FIB trimming of *e*-beam patterned T-shaped junctions. Perpendicular nanocontacts were made either by FIB milling conical nanopores through a 100-nm-thick silicon nitride membrane, in a similar process to that used by Ozatay *et al.*¹⁶ or by nanoimprint lithography using an atomic force microscope (AFM) tip in a simplified version of the method described by Carrey *et al.*¹⁹ As it has been suggested that the large magnetoresistance values¹ may be a result of a nonconducting dead layer at the contact, nanocontacts were also prepared in which the bottom contact was oxidized prior to depositing the top contact. Details of the preparation procedures are given elsewhere.²⁰

FIB cross sectioning and scanning electron microscopy (SEM), transmission electron microscopy (TEM), and AFM analyses showed that sizes of the contacts fabricated by the different methods ranged from 1 to 30 nm. The nanocontacts prepared by nanoindentation were typically 10–20 nm wide. Those prepared by FIB milling of the T junctions were 20–30 nm in width. The smallest ones, prepared in conical membrane nanoporations, were less than 3 nm in size. These structures are illustrated in Fig. 1.

Figure 2 shows typical magnetoresistance curves for the three types of nanocontact. Figure 2(a) shows the data for a sample prepared by FIB milling of a planar T junction, Fig. 2(b) shows the results for a junction made by the AFM nanoimprint method, and Fig. 2(c) shows the data for a conical membrane nanoporation whose resistance is 349 Ω. Magnetoresistance values are 0.4%, 0.5%, and 3%, respectively. The latter is the largest we observed in any of 30

^{a)}Electronic mail: jcoey@tcd.ie

FIG. 1. Secondary-electron images of (a) a FIB-trimmed *e*-beam patterned nickel T junction and (b) a FIB-milled conical nanopore in a 100-nm-thick silicon nitride membrane viewed in cross section and from the top and bottom surfaces of the membrane.

samples. For the FIB milled T junction, the magnetic field was applied perpendicular to the top of the T bar, while for the other contacts the field was parallel to the film plane.

The formula of Sharvin²¹ and Jansen *et al.*²² for the resistance of a ballistic nanocontact is

$$R_c = \frac{8h}{e^2 d^2 k_F^2}, \quad (1)$$

where k_F is the Fermi wave number and d is the contact diameter. For Ni, we suppose that there are 0.6 electrons in a free-electron band. Taking the electron density $n = 5.5 \times 10^{28} \text{ m}^{-3}$ and $k_F = 1.2 \times 10^{10} \text{ m}^{-1}$, the relation between diameter and resistance can be written as

$$d = \frac{37.9}{\sqrt{R_c}} (\text{nm}). \quad (2)$$

Using Eq. (2), the contact sizes calculated from R_c are 10.9 and 5.3 nm for the imprint and the FIB-milled T nanocontacts. The 10.9 nm value agrees with that determined experimentally. However, SEM imaging during the FIB milling of the T nanocontacts indicated a contact size that was twice the calculated value. This difference may be because the tails of the ion beam may have sputtered away the nickel at the edges of the FIB cuts, thereby reducing their width. The diameter of the membrane contact of Fig. 2(c) is calculated to be 2.0 nm, which is consistent with the SEM observation. The *I*-*V* curves for all these nanocontacts were Ohmic, which indicates that no oxide tunnel junction was formed at the interface even though the samples were exposed to air between the sputtering of the two nickel layers. As it has been suggested that large magnetoresistance may be due to a magnetic dead layer, samples were prepared by the membrane and imprint methods where the bottom nickel layer was plasma oxidized prior to the sputtering of the top layer. The *I*-*V* curve of an oxidized membrane contact showed a nice tunneling characteristic, which was fitted to the Simmons equation²³ to yield a barrier height and width of 2.7 eV and 0.9 nm, respectively. The form of the magnetoresistance curves was identical to those for the Ohmic contacts, but with values of less than 1%.

How can we explain the observed magnetoresistance in the three types of nanocontact? The effects are all small, of

FIG. 2. Magnetoresistance curve of (a) FIB-trimmed *e*-beam patterned T nickel contact, (b) nickel contact made by AFM nanoimprint, and (c) a nickel contact formed in a nanopore made by FIB milling through a silicon nitride membrane.

the order of 1%, but negative in the planar FIB-milled T and positive in the two nanopores (Fig. 2). There is no evident difference in magnetoresistance between the Ohmic contacts and the tunnel junction.

Starting with the T [Fig. 2(a)], we expect that the two arms are initially magnetized initially along their axes, at 90° to each other. If the magnetization M in the arm subject to the transverse field is oriented at an angle θ to the long axis, then $\sin \theta = H/M$, if the magnetization is uniform. The anisotropic magnetoresistance is given by $R = R_0 + \Delta R \sin^2 \theta$, where $\Delta R/R = -3\%$ for Ni. The resistance is greater when the magnetization is parallel to the current than when it is perpendicular, and the effect saturates at $H = M$. This quadratic variation can be discerned below the sharp peak in Fig. 2(a). That it saturates at 0.2 T, instead of at $\mu_0 M = 0.6 \text{ T}$ expected for nickel, is probably a reflection of a nonuniform magnetization state in the narrow zone at the contact that contributes most to the resistance.

The sharp feature in all three samples in Fig. 2 indicates switching of the magnetization in a low field of about 5 mT. In the nanoporations, it is expected that the magnetization of either the top or the bottom film reverses, but it is difficult to see how this could entail a change in direction of magnetization in the contact from parallel to the current to perpendicular to it. Such a change would be needed to observe the full anisotropic magnetoresistance of nickel [Fig. 2(c)]. The sharp feature in the magnetoresistance may well be ballistic, but it is not very big, even in the case of the tunnel contacts across which exchange coupling must be weak. It seems that the *spin configuration* on either side of the nanocontact is little influenced by relative orientations of the magnetization of the two films. This may reflect the relative importance of dipolar interactions compared to exchange in these small structures. Consider a conical nickel perforation in a 100-nm-thick membrane, which tapers from a radius of 50 to 2 nm. The exchange energy cost E_{ex} of reversing these bonds is $\pi d^2 A / 4a$ J, where A is the exchange stiffness (350^{-11} J m $^{-1}$) and a is the interatomic distance (0.2 nm). Hence $E_{\text{ex}} \approx (2.74\text{--}68.6) \times 10^{-17}$ J. The dipolar energy can be estimated by considering the interaction of the moment of the conical contact $m = \pi d^2 t M / 12$ (0.6×10^{-18} A m 2) with its image in the film at a distance of 130 nm. This is 5×10^{-18} J. The dipolar interaction in this case can trump exchange to produce antiparallel alignment of the spins across the contact. Switching the magnetization of one of the films simply creates or eliminates a domain wall in the thickness of the membrane, which will be too wide to produce much ballistic magnetoresistance, as this varies as δ_w^{-2} .²⁴

While this model is certainly oversimplified, it can explain why no huge ballistic magnetoresistance is observed in this type of contact. Atomic Monte Carlo²⁵ and micromagnetic^{26,27} simulations of different nanocontacts and nanoconstrictions indicate that there are vortex modes in small constrictions. Our own OOMMF simulations (Fig. 3) bear this out, and they show the antiparallel alignment of the spins on either side of the contact. Another issue is that thermally activated fluctuations between different magnetic modes are to be expected in constrictions smaller than about 10 nm at room temperature.²⁷

In conclusion, the sharp low-field feature in the resistance of nickel nanocontacts has been attributed to ballistic magnetoresistance. The smallness of the effect ($\approx 1\%$) in Ohmic or in tunnel-barrier contacts reflects the fact that dipolar interactions tend to impose an antiparallel spin alignment across the contact, which is little influenced by the magnetization direction of the electrodes. To observe a large ballistic magnetoresistance, which requires a sharp and switchable change of relative magnetization direction across the contact, it is necessary somehow to reduce the importance of dipole coupling of the spins across the nanocontact; it is absent, for example, in smooth planar tunnel junctions.

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FIG. 3. Micromagnetic simulations of the magnetization of a conical nickel nanocontact between two planar electrodes with increasing applied magnetic field (-10 , 0 , 3 , and 10 mT).

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