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Artifacts that mimic ballistic magnetoresistance

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Abstract

We have investigated the circumstances underlying recent reports of very large values of ballistic magnetoresistance (BMR) in nanocontacts between magnetic wires. We find that the geometries used are subject to artifacts due to motion of the wires that distort the nanocontact thereby changing its electrical resistance. Since these nanocontacts are often of atomic scale, reliable experiments would require stability on the atomic scale. No method for achieving such stability in macroscopic wires is apparent. We conclude that macroscopic magnetic wires cannot be used to establish the validity of the BMR effect.

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Theoretical physics suggests that extremely large magnetoresistance (MR) might be found in certain magnetic nanocontacts if a magnetic domain wall could be localized in the nanocontact on a length scale that would allow conduction electrons to transit the wall ballistically [1]. Recently, several experimental reports of extremely large MR values have been published and claims have been made that these results are due to a ballistic magnetoresistance (BMR) effect [2,3]. Published reports suggest that BMR values as large as 1,000,000% may occur [3].

If the very large BMR values are real, it would have enormous implications for the hard-disk drive industry. Read heads that are now based on the giant magnetoresistance (GMR) effect might soon be replaced by ones based on a far larger BMR effect. Such heads would likely be able to read far smaller magnetic bits.

We have carried out an extensive search for evidence of a BMR effect in magnetic nanocontacts [3]. We have investigated both thin-film and

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thin-wire geometries for both mechanically formed and electrodeposited nanocontacts. We find no systematic differences between mechanically formed and electrodeposited nanocontacts. The samples we have investigated include mechanical contacts between ferromagnetic wires, electrodeposited nanocontacts between ferromagnetic wires, ferromagnetic nanocontacts electrodeposited on Cu wires, nanocontacts electrodeposited between ferromagnetic films anchored on wafers, ferromagnetic nanocontacts electrodeposited on Cu films anchored on wafers, nanocontacts between two ferromagnetic films connected by a pinhole through an insulating film, and nanocontacts formed by focused ion-beam etching. We did not find credible evidence to support the existence of a real BMR effect. However, we did find a number of artifacts due to magnetostrictive, magnetostatic, and magnetomechanical effects that could mimic BMR.

Fig. 1a presents one geometry in which BMR has been reported and illustrates the magnetostatic force produced by parallel alignment of magnetic wires [5]. Since the Ni wires are anchored at their ends, they will stretch in response to the force. If each Ni wire is 4 mm long, it is a simple calculation, using the modulus of elasticity, to predict that each wire will lengthen ≈ 1 nm if the ends are hemispherical and 3 nm if flat. In antiparallel alignment, each wire will shorten by the same amount. Thus, from parallel to antiparallel the total length change will be from 4 to 12 nm. Since BMR nanocontacts are generally thought to have dimensions on the order of a single atom to a few nanometers, such length

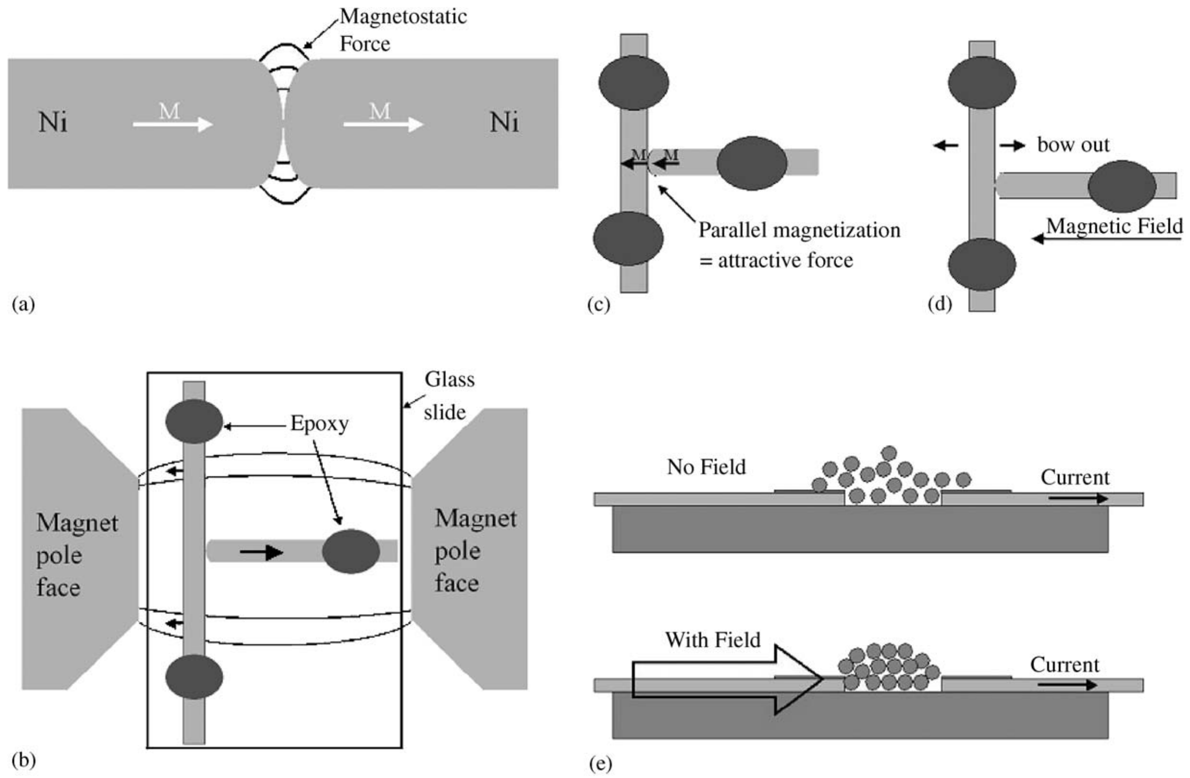

Fig. 1. An illustration of the artifacts we have found that can mimic BMR. They are: (a) magnetostatic attractive force in a linear geometry; (b) magnetostriction and the attraction of a fringing field in a "T" geometry; (c) the magnetostatic attractive force in the "T" geometry; (d) the bowing out due to the increase in length in the transverse wire; and (e) the clumping together of a granular assembly of magnetic particles.

changes could severely distort the nanocontact and give resistance changes that could be mistaken for true BMR.

Fig. 1b illustrates the so-called "T" geometry used for some BMR studies [3]. This geometry is subject to the artifacts shown in Figs. 1b–d. When the magnetic field is applied, magnetostriction will shorten the axial wire in Fig. 1b as illustrated by the black arrow. If the axial wire is Ni and 4 mm long the shortening is calculated to be 136 nm. Another possible artifact is the attraction of the transverse wire by the fringing field of the magnet. The magnitude of this effect will be very much sample-size dependent, and is illustrated by the two arrows pointing to the left in Fig. 1b (the sample size is much exaggerated here for clarity).

Fig. 1c illustrates the magnetostatic force similar to those of Fig. 1a but in the "T" geometry. This force can compress a nanocontact and lower its electrical resistance. Fig. 1d illustrates the bowing-out artifact that will be present for a very straight transverse wire. A transverse wire will lengthen due to the transverse magnetostriction effect, and if the ends are fixed, it will tend to bow out in some direction. The bowing out can be surprisingly large and in any direction [4].

We have found that the artifacts in Figs. 1a–d can lead to infinite MR. The effect is, of course, not BMR but the breaking and reforming of the nanocontact. See Ref. [4] for details.

Fig. 1e illustrates another type of artifact that can occur when a nanocontact is electrodeposited at an unusually high potential [3]. A granular deposit of ferromagnetic particles results. Under the influence of a magnetic field, the particles are magnetized in parallel and tend to clump together forming a more intimate contact that lowers the electrical resistance. This motion is visible in an optical microscope [6].

Fig. 2 presents three of the simplest forms that the data take when using the "T" geometry. These samples were nominally prepared in the same way. Inadvertent and innocuous differences in mounting the wires appear to lead to different artifacts or a different mix of artifacts dominating the data.

We feel confident that the data of Fig. 2 do not result from BMR since, as published previously [4], we sometimes found infinite MR with curves

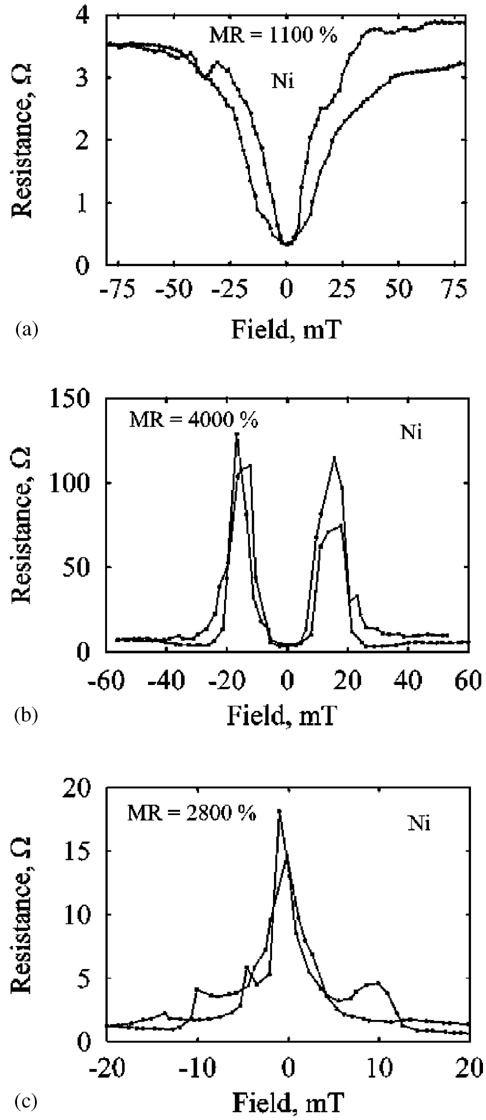

Fig. 2. Three different generic types of data obtained on Ni samples in the "T" geometry, illustrating how inadvertent differences in sample mounting can lead to quite different artifacts dominating the data.

that had the same qualitative shapes as in Fig. 2. Breaking of the nanocontact was responsible. The most reasonable explanation of Fig. 2 data is that the magnetomechanical forces did not quite break the nanocontact but merely distorted it.

We should emphasize that if we wanted to make a credible case for a real BMR effect it would be easy to do so by presenting only a typical data such as those in Fig. 2. The data in Fig. 3, however, are much more typical of what is obtained in the “T” geometry than the data of Fig. 2.

In Fig. 3, we present data on a sample made of low-magnetostriction permalloy wire to make the point that magnetostriction is clearly not the only force moving the wires. Magnetostatic forces are sufficient to distort the nanocontacts and produce very large changes in electrical resistance.

Much of our data (e.g., Fig. 3) are more complicated than the simple plots that are commonly published. When the sample of Fig. 3 is cycled in the magnetic field, the shape of the data changes gradually from panel to panel. The only changes in the contact are the result of field cycling and the passage of time. The sequence runs from the top-left panel to the bottom-left panel then from the top-right panel to the bottom-right panel.

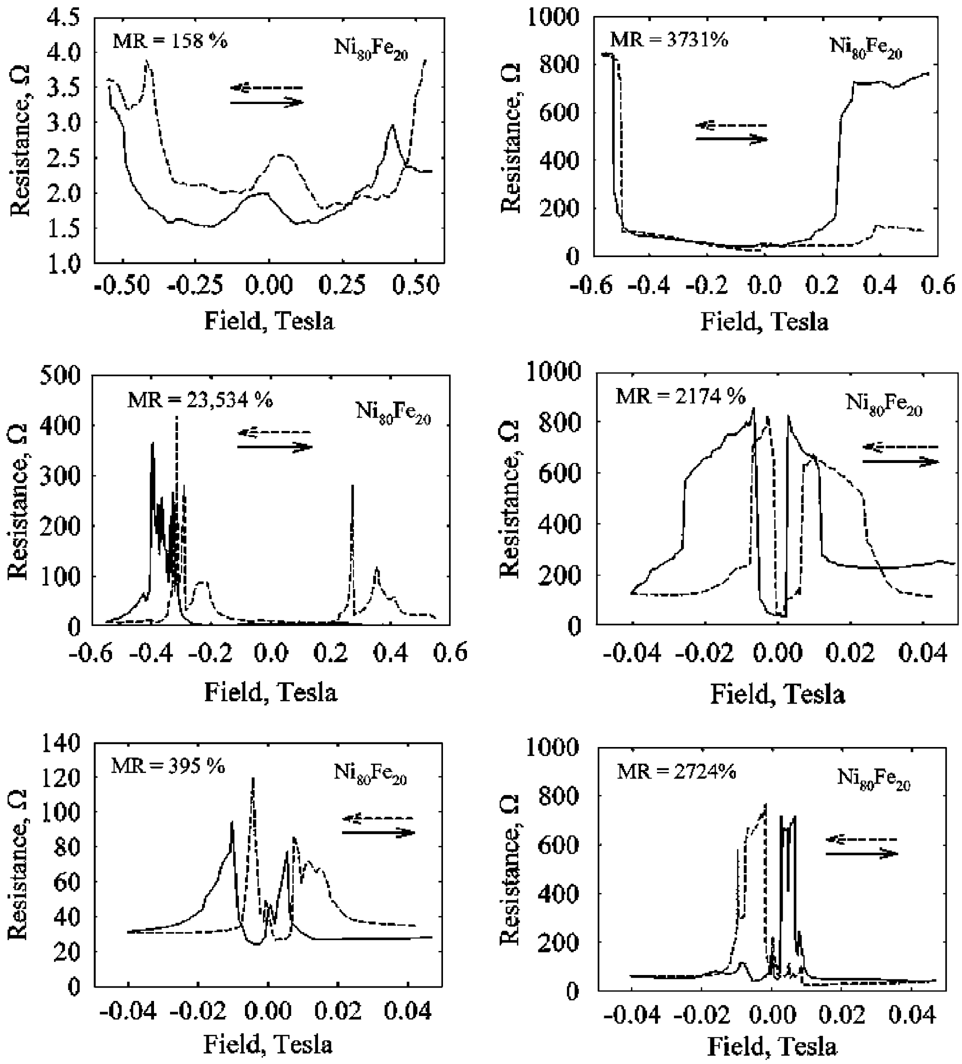

Fig. 3. An illustration of the type of data that is often obtained in the “T” geometry of Figs. 1b–d. These data were taken serially on a single sample, proceeding from the top-left panel to the bottom-left panel then from the top-right panel to the bottom-right panel. Permalloy is used for this sample to illustrate that even without magnetostriction, magnetostatic forces can move the wires around. In our measurements, complex results such as these are more common than the simpler data in Fig. 2.

On average it takes about ten field cycles from one panel to the next as the shape of the MR curves gradually changes.

During such cycling, the data will occasionally exhibit one of the simple shapes illustrated in Fig. 2. In some samples, one of the simpler shapes will appear for a number of cycles.

While it might be tempting to interpret such simpler data as real BMR, we think that such a step would be unjustified. The data of Fig. 3 are most plausibly interpreted as wires moving around or rubbing against each other to change the size and shape of nanocontact(s) between them. We conclude that the "T" geometry is so prone to artifacts that it cannot be used to provide credible evidence for a real BMR effect.

One final point that should be made about the "T" geometry is that we cannot find any pattern in the data to distinguish between electrodeposited and mechanically formed nanocontacts. As far as we can tell, the results are indistinguishable.

We have designed and fabricated samples in geometries that avoid the artifacts in Fig. 1, but none shows any credible evidence for BMR [4]. While it is impossible for us to prove that artifacts occurred in the publications reporting large BMR values, our work strongly suggests that possibility. Therefore, we conclude that it is entirely possible that there is no real BMR effect of any significant magnitude in any data published so far.

Future attempts to identify a real BMR effect should concentrate on designs that stabilize the nanocontact at sub-atomic length scales. Readers may consult Ref. [7] for one approach to this challenge.

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