Magnetostriction Measurements with Atomic Force Microscopy: A Novel Approach

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In this study we present a new method of measuring magnetostriction with an atomic force microscope adapted for the application magnetic fields. The experiment allows us to visualise, in an elegant and educational way how the lateral magnetoelastic shape changes take place on the sample surface when a magnetic field is applied. We have, furthermore, used this technique to observe magnetically induced strains as small as $5 \cdot 10^{-8}$, and have measured Ni, permalloy and commercial Cu wires and films, as well as pure Cu and Pt wires, where results are in agreement with other methods of measurement. The applications are, moreover, relevant to studies of ballistic magnetoresistance, where we can draw conclusions involving the effect of the magnetically induced strains on magnetoresistance measured at the same time as magnetostriction.

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Magnetostriction is the phenomenon whereby the shape of a ferromagnetic specimen changes during the process of magnetization. [1] The deformation $\Delta l/l$ resulting from this change is usually in the $10^{-5}$ to $10^{-6}$ range. Magnetostriction can be positive or negative depending if the material expands or contracts along the measured direction. [2] Many ways exist for measuring this field-induced deformation, including the strain gauge and capacitance methods. [1–5] The development of local surface probes (scanning tunnelling microscopy (STM), scanning force microscopy (SFM), magnetic field microscopy (MFM) and others) [6,7], however, has introduced new ways to visualize the structure and topology of the surfaces with high spatial resolution. These surface characterization techniques can easily visualize variations of the surface structure as well as local surface behaviour such as those resulting from induced strains on the measured specimen. Takata et al, in particular, have reported strain imaging of magnetic recording material. [8] By their definition, however, strain imaging involves detecting strains generated by any modulation including an alternating magnetic field. In the case of Ref. 8, the strain is driven in the z-direction by the alternating B-field. Up to now, and according to our knowledge, there have never been applications of local probe techniques to observe and measure lateral changes of the shape of a specimen under an applied magnetic field without modulation. Given the vast applications of magnetic materials, the need for magnetic characterization methods of greater resolution is paramount. We, therefore, believe that carefully set-up experiments of this nature should provide very valuable information.

On another note, ever since preliminary experiments showing large ballistic magnetoresistance (BMR) effects in atomic nanocontacts have been reproduced in other cases, [9–11] there have been observations of BMR values of 700%, [12] 3000% and practically infinity. [13] The latter are observed when Ni contacts of nanometer size are electrodeposited in the gap region of Ni wires. In addition, BMR values of over 50000% have been observed when using permalloy Fe$_{21}$Ni$_{79}$ wires, and values not as large (a few hundred percent) [14] were measured in commercial Cu wires. From the above, a very legitimate question can be posed: What is the effect of the magnetostriction deformation of the nanocontacts on the
**BMR? In other words, is the BMR due to the magnetoelastic deformations?**

In this paper we present a new method of measuring magnetostriction with the use of atomic force microscopy (AFM). With the AFM we are able to visualize in an illustrative and educational manner the strains of a ferromagnetic sample’s micro and nanostructure under an applied magnetic field. In our technique, the field is unidirectional for each application with the intended value applied near-instantly and removed in the same manner after a period of influence lasting several seconds (and scan lines). There is no field modulation, and the lateral shift is measured directly from the scan. Lateral strains as small as $5 \cdot 10^{-8}$ have been thus measured, although this resolution could be improved under more stringent scanning conditions. Sample size, however, is not an issue as long as a topographic image can be attained. Thus, the technique is easily applicable to samples whose length is of the order $100 \, \mu m$ as well as larger specimens. The wires measured in this study included Ni, permalloy, commercial and pure Cu as well as Pt. In addition, applications of this method are performed to answer the question posed above by measuring BMR of nanocontacts formed via electrodeposition on wires. From our results: we do not see a direct relation between magnetostrictive strains and large BMR.

The experiment was conducted with a Dimension 3100 Scanning probe Microscope (SPM), with a Nanoscope IV Controller. Figure 1(a) shows a diagram of the experimental set-up during measurements. The U-shaped electromagnet (constructed in the laboratory for this purpose) was comprised of a ZnMn ferrite powder core, wrapped with Cu wire on one end. The magnet was, furthermore, supported so the poles could be accurately placed on either side of the sample (without coming into contact with the latter), with the desired stability during scanning. This configuration provided a maximum field of about 250 Oe (measured with a DTM-133 Teslameter at the sample plane) for these measurements. By controlling the current of the 75 W, DC power supply, the magnetic field strength could be varied to within $<2$ Oe.

The metal wires used were Ni, permalloy Fe$_{21}$Ni$_{79}$, Cu (both commercial wire and that of 99.999% purity) and Pt. With the exception of Ni, with a diameter $d = 0.25 \, \text{mm}$, all
the metal wires were of \( d = 0.5 \text{ mm} \). Fig.1(b) shows, in diagrammatic form, how the wires were attached to their base (made of circuit-board material) for both the cases of free wires and wires in a “T”-configured contact formation (upper and lower diagrams of fig. 1(b) respectively). Cyanoacrylic commercial glue was the preferred sample clamping method, used successfully in all cases. The glue was applied to a length \( l^2 \) at one end of the wire, leaving a predetermined length \( l^1 \) free. The distances from the glue boundary to the AFM tip for each wire were measured using an OLYMPUS BX50 optical microscope in combination with the built-in optical microscope camera of the Dimension 3100 SPM.

Figure 1(c), shows a side-view close-up of the scanning process. Contact mode AFM was always used, with short (100 \( \mu \text{m} \)) cantilevers with a force constant of 0.58 N/m being preferred. Fig. 1(c) schematically depicts the case of a free wire measured under a field direction parallel to its length. The scan direction was always along the length of the wire, whereupon changes in the length were easily detected as shifts in the x-direction of the scan image.

**Ni free wires and “T” – configured contacts:** Our first measurements were conducted on Ni, a ferromagnetic material with well-known magnetoelastic properties. Wires were measured in two configurations: a) single free wires and b) two wires forming a “T” configuration (fig. 1(b), lower portion). Results are depicted in fig. 2. Specifically, the upper portion of fig. 2 shows two typical scans of the Ni wire surface (left and center) using contact mode AFM, and an optical microscope close-up image of the measured “T”-configured contact (right). The two scans are both 300 nm in range with the positive x-direction toward the right of each scan. In the case of the far left scan the magnetic field (\( H = 80 \text{ Oe} \)) was consecutively applied and removed five times. The scan direction (as indicated by the vertical arrow) was from the bottom to the top of the image, and the first application of the field (toward the bottom of the scan), including the direction of strain, is depicted by the black arrow pointing left (indicating contraction). In contrast, the bottom portion of the figure shows the arrow pointing right, which is indicative of the field being turned off (re-expansion to original length). As can be easily seen in the far left-hand scan of fig. 2,
the shift is nearly instantaneous whether the field is applied or removed, i.e., there are no distortions of the scan image during magnetic field transitions. The distance of the shift was easily measurable using available SPM software, and the repeatability of the effect is easily demonstrated by the identical multiple shifts in the scan. Another important result is that when the field is removed the wire returns to precisely its original position as indicated by the topographic continuity observable in the far left image between field applications. The contrast between the far left-hand scan and that at the upper middle of Fig. 2, where no field is applied is obvious, although the scans do not show identical topographic features (scan windows are within 1 m of each other on the surface). Even with images with a great degree of noise, the effects of magnetoelastic strain are easily distinguishable from the former at least for strains down to $5 \cdot 10^{-8}$.

The bottom portion of fig.2 depicts the results of various measurements of different configurations of Ni wires under the influence of both parallel and transversal fields, where changes in field intensity reach 250 Oe. The upper portion of the graph (fig. 2(a)) depicts the changes in length of a 6 mm free wire during the indicated field application when field direction is transversal to the length of the wire, while the lower portion (fig. 2(b)) shows the magnetostiction of a 6mm free wire when the same field values are applied in the direction parallel to the wire’s length. The extra data points on the right-hand side of both plots represent singular values of wire deformation measured under different sample mounting and field direction conditions. The plot (represented with inverted solid triangles) in fig.2 (b), represents the deformation of the “T”-configured Ni contact vs. increasing field strength. First, the plots of the deformation of the free wire vs. field strength for magnetic field directions both parallel and transversal to the wire lengths have been presented elsewhere, [15] and are in agreement with previous findings for the magnetoelastic deformation of Ni wires under a field direction parallel to their length. [1–3] Second, the question whether the glue itself provides adequate clamping to prevent movement of the wire as a whole when under a magnetic field, and thus eliminates the strain effects caused by the total magnetization of the specimen was addressed by first measuring the strain on a wire where
the glued portion was five times the length of the free (1 mm) wire. We found the deformation to be twice that of a wire with only 25% of its total length glued (such as the wires used in the plots of Fig. 2 (a) and (b)). We then eliminated the strain contribution of the glued portion by measuring the magnetostriction at two points on the free wire, and applying the formula \( \frac{\Delta l_2 - \Delta l_1}{l_2 - l_1} \), where \( l_2 \) and \( l_1 \) are the free wire lengths corresponding to the two positions. Results deviated only 5% from the case of the wires glued along 25% of their total length, and could be improved with a smaller percentage of the total wire length glued. For a more detailed explanation see Ref. 15.

Our measurements continued with the magnetostriction of a 6 mm free Ni wire (only 2 mm glued) in a “T”-configured contact formation, with a contact area measured at 30 \( \mu \)m. The upper right-hand portion of figure 2 shows a 600 m Dimension 3100 optical microscope picture of the “T” contact area. The scans were performed 200 \( \mu \)m from the contact itself. With these measurements along with those on permalloy wire we attempt to shed some light on the relationship between magnetoelastic deformation in “T”-configured contacts and BMR. For this reason, the resistance was monitored over the contact throughout all the magnetic field applications involving “T”-configured contacts. The value of this resistance was measured at 1.5 \( \Omega \), which represents the effective conductive portion of the contact. From previous studies we have found this particular value to correspond to conducting contact of 30 nm, [14] in contrast with the total contact geometry (30 \( \mu \)m diameter area). Most of the total contact area is actually comprised of non-conductive oxides.

In fig. 2(b) the upper curve represents the deformation values of the “T”-contact vs. increasing magnetic field, up to 250 Oe in a direction parallel to its length. The observed deformation at 250 Oe is about half the value of the free wire (-16 nm/mm) when the field is parallel, and about 2.5 nm/mm when it is transversal to the wire’s length (represented by the hollow upright triangle in fig. 2(a)). In the case of the parallel field direction in particular, it would be expected that a 100 nm contraction (over the 6 mm free length) would break the contact. In fact, the monitored resistance remained stable during multiple consecutive field applications. In other words, magnetoelastic strain does not alter the resistance across the
contact, and more importantly does not automatically imply large magnetoresistance. It is most likely that both wires of the “T”-configuration in the contact area deform together when the field is applied. In other words, we must consider the contact connecting the two wires as a single system extending to the second wire.

It is known that 10% of the contact samples exhibit magnetoresistance in the 100% range and only 2% of the samples show BMR values over 1000% [12–14]. All ferromagnetic materials exhibit some degree of magnetoelastic deformation, including those exhibiting BMR. Although it is evident that magnetostriction does not necessarily imply BMR, we can draw no conclusions involving the reverse from the available data on Ni. But there is no evidence that the contacts are modified as indicated from our resistance and magnetostriction data. In other words, based on the above results, we cannot say one way or the other if BMR induces magnetoelastic strain.

*Permalloy Fe$_{21}$Ni$_{79}$ wires:* Similar measurements were conducted on permalloy Fe$_{21}$Ni$_{79}$, although only for the cases of the free wire and ”T”-configured contact both under the influence of an applied field parallel to the wire lengths. Figure 3 shows a similar configuration as that of fig. 2, this time of the permalloy “T”-configured contact. The top portion of the figure shows two scans of 450 nm of the wire surface, about 200 µm from the contact tip. The left-hand scan involves magnetic field applications, and the subsequent respective topographic shifts in the image, while the right-hand scan represents the surface without any magnetic field applied. Below these images is a graph showing the changes in length of a 10 mm permalloy Fe$_{21}$Ni$_{79}$ wire when increasing field values are applied in the parallel direction. Our measured contraction of permalloy wire with increasing field strength is approximately equal to that indicated in the literature, [2] where $\Delta l/l$ approaches -2 nm per mm length of wire at higher field values ($H \geq 80$ Oe). To examine the case for BMR applications, an additional data point (hollow circle) was added. This represents the measured contraction of the permalloy wire under an 80 Oe parallel field, when forming a contact (in a ”T”-configuration as with Ni). The permalloy contact also remained intact with a stable re-
sistance during deformation. The obtained value for the permalloy contact was, furthermore, practically identical to that of the free permalloy wire. In the case of permalloy Fe$_{21}$Ni$_{79}$, however, the movement is too small to meet resistance from the glue or transversal wire. It is most likely for this reason that we do not observe any decrease in the magnetostriction values of permalloy when comparing the field induced strain of the "T"-configured contact with that of the free wire.

**Copper and Platinum wires:** We conducted measurements on three paramagnetic wires, each 10 mm long with applied fields in directions parallel to their respective lengths, and have provided some interesting results. Commercial Cu was measured first, initially as a reference sample to the Ni and permalloy wires. Despite the fact that Cu is a paramagnetic material, there was magnetostrictive strain that increased with increasing magnetic field strength, although in a more linear manner than Ni and permalloy. The changes in length measured in the commercial Cu sample, moreover, were of the same order as permalloy wires under a parallel field. Figure 4 (top left) shows a case where a field is applied to commercial Cu with the evident shift (in the same manner as the previous ferromagnetic samples under parallel fields). The top right part of the figure depicts the plot of the contraction of the commercial Cu wire with increasing field strength, as described above. Our commercial sample was analysed by EDAX where the presence of 3% Co, Ni and Fe impurities was detected. It is evident from this analysis that even minute amounts of impurities cause appreciable changes in the values of magnetoelastic strain in a paramagnetic material such as Cu. To compare we have attempted to measure magnetostriction in pure (99.999%) Cu, as well as Pt wires (not shown here), and the scans do not exhibit any observable change under the same applied field (250 Oe). I.e. there is a complete absence of the characteristic topographic displacement in the x-scan direction present in measurements of ferromagnetic specimens. It should be noted that pure Cu actually exhibits a magnetostriction deformation of $10^{-9}$, which for a 10 mm of Cu wire implies a displacement of 0.01nm (0.1 Å) [16]. At the bottom right-hand of the figure is a scanning electron micrograph (SEM) of a Cu film with a 10 µm gap, bridged by electrodeposited permalloy, where we measured for BMR
and magnetostriction. While close to 100% BMR was measured here, (repeatable through several hundred trials), there was no observable magnetostriction under applied fields up to 250 Oe. The lack of displacement described for the pure Cu and Pt samples is clearly shown in the 200 nm scan of the aforementioned contact (fig.4, bottom left), where repetitive field applications were performed while scanning under the AFM. It is no surprise, regarding the above information, that a pure Cu film shows no magnetostriction. The permalloy deposite should, however, also be taken into consideration. As we have described, permalloy Fe$_{21}$Ni$_{79}$ exhibits a magnetostrictive strain around $10^{-6}$, which implies a strain of 0.01 nm (0.1 Å) for a 10 µm length of the material. We have attempted to see this displacement with an ex-situ STM, but resolution was in the Angstrom range, and no topographic shifting was detected. It is noteworthy that even a displacement below what is the minimum detectable causes a disturbance in the scan that manifests as a horizontal line through the image at the point the field is applied. Whether, however, this 0.1 Å displacement of the contact can influence the BMR response can be understood as follows: Our 1-10 Ohm contacts correspond to sections of contacts of $10^3$ to $10^4$ atoms- taking one atom to be one conductance unit for a good conductor (for a bad one the section is larger still). In order to obtain the observed changes of 200% such as those described in the case below, we would need to change the section by a factor of 3. This, according to all simulations regarding the pulling of nanowires, is not possible for a shift of 0.1 Å.

We thought it relevant to conclude this report with a brief description of our most recent magnetostriction data (not shown here), involving the measurement of a contact formed by the electrodeposition of permalloy to bridge the 30 µm gap between two pure Cu wires aligned tip-to-tip [17]. The applied field strength in this case was $H = 850$ Oe, and no shift was observed in the scan upon field application, meaning that if there was a strain present it was $<5 \cdot 10^{-8}$. As described in the former paragraph, such a strain cannot correspond to the measured BMR of 200% in this system. From the very fact that we did observe BMR in at least these two latter cases, we may conclude that not only does magnetostriction not imply BMR, but that also the presence of BMR does not mean observable magnetostriction.
is present. The two effects are thus not related to each other.

In this report a new method of measuring the magnetostriction of metallic wires has been presented, which utilizes atomic force microscopy (AFM), and the (near-instantaneous) application of a magnetic field at the sample plane. The strains are observed laterally, relative to the sample plane, in the direction of the scan in progress. This technique eliminates the contribution of strains due to magnetization of the total specimen, and the lack of modulation guarantees the absence of electromagnetic effects due to eddy currents caused by the effects of the oscillating magnetic field on the sample. We have measured strains as small as $5 \cdot 10^{-8}$ in sample areas in scan ranges as small as 200 nm. The experiment shows in a dramatic visual manner how the magnetoelastic strains of the sample take place when the magnetic field is applied. For wires exhibiting magnetostriction, the shift is instantaneous and is clearly depicted in the scanned images presented in this study. Applications of this method have been made to wires of Ni, permalloy, commercial Cu wire, pure Cu, and pure Pt, as well as “T”-configured contacts of Ni and permalloy Fe$_{21}$Ni$_{79}$. These applications are relevant in examining the effect of magnetoelastic strains on magnetoresistance, measured at the same time as the magnetostriction. From the data presented, there is no evidence that magnetostriction automatically implies magnetoresistance. While large magnetostriction is seen for all Ni samples, magnetoresistance is only seen for the 10% of the samples and only 2% for BMR larger than 1000%. This happens for Ni and permalloy samples even if the deformations of the latter are 30 times smaller than those of the former. We speculate, as discussed above, that the contact moves rigidly with the magnetoelastic motion of the wires (as if the contact and second wire are a continuation of the first). Further measurements on permalloy contacts deposited on pure Cu films and wires, which have exhibited up to 200% BMR have shown no observable magnetostriction. We, therefore, conclude that BMR and magnetostriction are not causally linked, i.e. one effect does not imply the other.

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Figure Captions:

Figure 1: Schematic depicting the experimental set-up with (a) a top-view diagram of the Dimension 3100 SPM with the sample holding system placed between the poles of the electromagnet inserted under the scanner (shown transparent). (b) Top-views of free wire and contact configurations, and (c) a side-view schematic of the placement of the AFM tip as it scans the wire.

Figure 2: top-left and center: Two scans of the Ni free wire with a magnetic field, applied multiple times throughout the scan, (left) and without any field applied (right). In both cases the scan range is 300 nm, while the scan direction is indicated by the red and black arrows in the corresponding figures; (top right): Dimension 3100 optical microscope image of Ni ”T”-configured contact after parallel field applications. Scale is in m. Contact area has been measured at 30 µm. (Bottom): Graphs of the measured change in wire length ∆l/l x10⁶ vs. the strength H (in Oe) of the applied field when (a) the field direction is transversal and (b), when it is parallel to the wire’s length. Upper plot of (b) refers to Ni contact and the lower graph to the free wire. Additional data points mark cases of magnetostriction for a contact under a transversal field (upright hollow triangle), and the case of a 1mm free wire under a parallel field (filled circle).

Figure 3: Top: two 450 nm contact AFM scans of permalloy Fe₂₁Ni₇₉ wire in ”T”-contact formation, with free length l = 10mm. Left scan shows the application of a magnetic field, while right scan depicts the same topography without any field applied. Bottom: Graph of ∆l/l x10⁶ vs. H with applied parallel field onto 10 mm free wire. Extra data point at H = 80 Oe (enlarged hollow circle) represents permalloy ”T”-contact deformation at this field strength.

Figure 4: Top row (left): 200 nm scan of a commercial Cu wire with a free (unclamped) length of 10 mm with an applied filed of H = 250 Oe. Topographic displacement to the left upon field application is obvious. Top row (right): graph of ∆l/l x10⁷ vs. H (in Oe),
with various field strengths applied in the parallel direction. Bottom left: 200 nm scan of permalloy electrodeposited over a 10 m gap in a pure Cu film. The scan was taken at a distance of \(~200 \mu m\) from the center of the gap. Even with multiple applications of a 250 Oe field, there was no magnetostriction evident. Bottom right: SEM photo of the latter surface showing a close-up of the contact area formed by electrodeposited permalloy. The 5 \(\mu m\) scale-bar is placed vertically to the right of the contact. This specimen, while showing no magnetoelastic response did exhibit a 100% BMR (both were measured at the same time).
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