Effect of bar width on magnetoresistance of nanoscale nickel and cobalt bars

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The anisotropic magnetoresistance (AMR) of nickel and cobalt bars of 1 μm length, 35 nm thickness, and width varying from 50 to 500 nm is studied. As the bar width is reduced from 500 to 50 nm, longitudinal MR change decreases from 0.8% to 0.2% and transverse MR change increases from 1.3% to 1.8% for the Ni bars; longitudinal MR change is zero and transverse MR change is constant at 1.6% for the Co bars. The zero longitudinal MR is attributed to a single-domain magnetization. The AMR value indicates that the electron scattering from bar edges has little effect on AMR even in a 50 nm width. Furthermore, strong, repeatable Barkhausen noise is observed in the Co bars with a width larger than 200 nm, which can be explained by a micromagnetic model. [S0021-8979(97)63008-X]

Patterned magnetic nanostructures are of great interest in understanding micromagnetics and developing ultrahigh density magnetic storage. A number of studies have revealed the size effects on the coercivity or magnetization reversal behavior of ferromagnetic thin films laterally down-sized into the submicron regime.[1–6] However, the magnetoresistance (MR) behavior of nanoscale ferromagnetic structures, which is important for future design and optimization of miniature MR read heads, is not well understood. Previous studies have found that discrete switching events become important and cause large Barkhausen noise in the MR response of multilayer submicron stripes.[7] In contrast, the MR response of single-layer submicron ferromagnetic stripes so far reported [Fe (Ref. 8) and FeNi (Ref. 9)] is rather smooth. In this work, we study the MR response of nanoscale Ni and Co bars and compare their different behavior. It is found that Barkhausen noise is significant only in the Co bars at width larger than 200 nm. The anisotropic MR (AMR) effect is measured in this study and results show that the longitudinal MR response of Co bars is flat as expected for a uniform magnetization along the bar length but that of Ni bars is not, as has been found in submicron Fe and FeNi stripes.[8,9] It is also found that the AMR ratio remains close to that of the bulk element when reducing the bar width to as small as 50 nm, which is important for ultrasmall MR read heads.

Thin-film Ni and Co bars of 50–500 nm in width are fabricated by using e-beam lithography and lift-off technique.[10] In the sample fabrication, a polymethylmethacrylate (PMMA) resist was first spun onto a SiO_2 substrate. Patterns of rectangles were exposed in the PMMA using a high resolution e-beam lithography system. The exposed PMMA was removed during development creating a resist template on the substrate. Then a Ni or Co film of 35 nm thickness was evaporated onto the entire sample using an electron evaporator. Finally, the resist was dissolved in acetone, lifting off the metal film on top of the resist and leaving the rectangular Ni or Co bars on the substrate. In this work, the bar length is 1 μm but the bar width varies from 50 to 500 nm. Current and voltage leads are arranged at the two ends of a bar as shown in Fig. 1.

Room temperature MR measurements were performed with a constant current passing through two leads along the bar length. The resistance was obtained by measuring the voltage drop across the other two leads. An in-plane magnetic field was applied either parallel or perpendicular to the bar length for longitudinal and transverse MR measurements, respectively.

Typical MR response curves are shown in Fig. 2 for the Ni bars and Fig. 3 for the Co bars. The MR change of Ni bars as a function of the width is measured and shown in Fig. 4. It can be seen that longitudinal MR change is small, decreasing from 0.8% at 500 nm width to 0.2% at 50 nm width. The transverse MR change increases from 1.3% at 500 nm width to 1.8% at 50 nm width. In contrast, Co bars show a zero longitudinal MR change and a constant transverse MR change of 1.6%.

Besides the MR change, it is found that all Ni bars have rather smooth MR response curves. But resistance jumps that are very repeatable have been recorded in the MR response

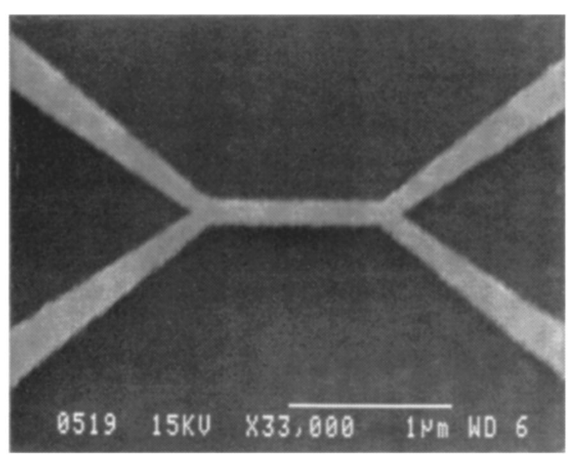

FIG. 1. SEM image of a 100-nm-wide Ni bar.

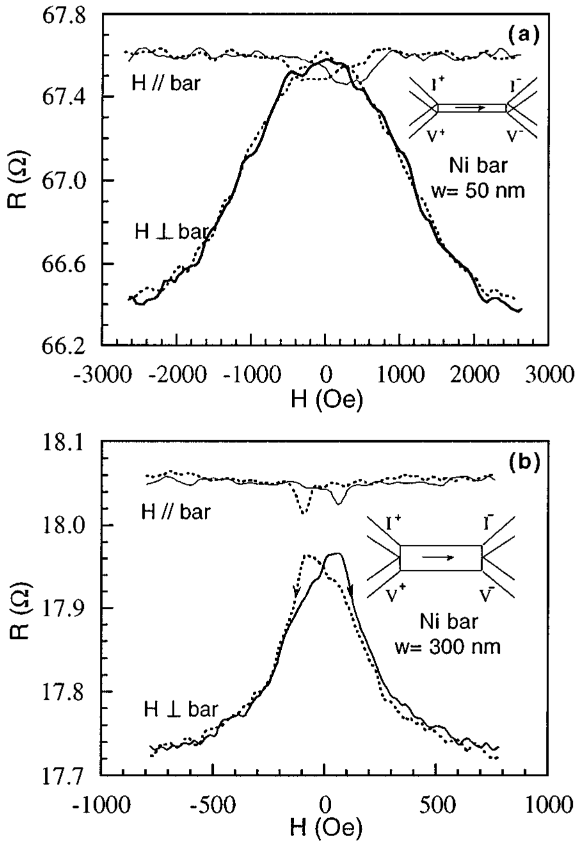

FIG. 2. MR response curves of Ni bars: (a) 50 nm width; (b) for a 300 nm width.

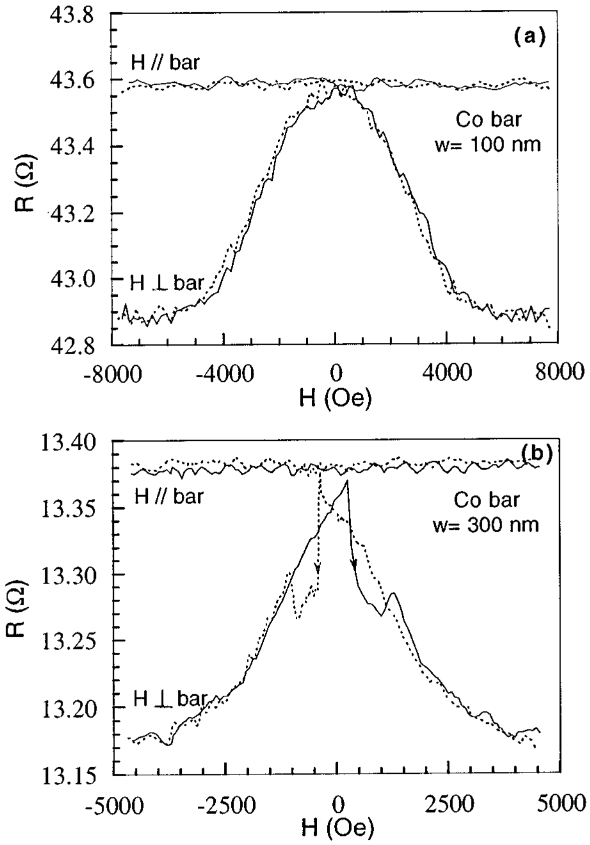

FIG. 3. MR response curves of Co bars: (a) 100 nm width; (b) 300 nm width.

curves of Co bars of 200 nm width or wider. As seen in Fig. 3(b) for a 300 nm Co bar, there is a sharp drop at ~300 Oe and then a sudden rise at ~1100 Oe. These jumps occur after the applied magnetic field reverses in direction. If sweeping the field in a loop from zero to the saturation, i.e., without alternating field direction, a smooth MR response is then shown.

A zero longitudinal MR change can be well understood for the Co bars. Since the bar width is much below a domain wall size, one would expect a single domain formation with the magnetization direction along the bar length. Therefore, for all values of the field in the longitudinal MR measurement, the magnetization keeps parallel to the current direction and for this situation there should be no longitudinal MR change.[11]

The nonzero longitudinal MR effect in the Ni bars (similar effect has been reported for submicron Fe wires[8] and NiFe wires as narrow as 0.2 μm[9]) suggests a nonuniform magnetization at low field. Because a Ni bar has a smaller shape anisotropy energy than a Co bar of the same geometrical dimensions, it is understandable that the Ni bar is not a single domain at low field. Besides, there are four leads at the bar ends which should affect the magnetization state of the bar. The leads are made of the same material as the bar and their length is a few microns from the bar end to a neighbor bonding pad of Ti/Au. However, the resistance of the bar can be measured accurately and independently of the lead effect.

Concerning the transverse MR change, the Co bars show a constant value of 1.6%. For a single domain bar, this gives the AMR ratio. The AMR ratio is determined by the difference between the saturated resistance at high transverse field and that at high longitudinal field.[11] Since a single domain bar has a constant resistance with longitudinal field and the transverse MR change is actually the difference between the saturated transverse and longitudinal resistance (as shown in Fig. 3) we find the AMR ratio as 1.6% for the Co bars.

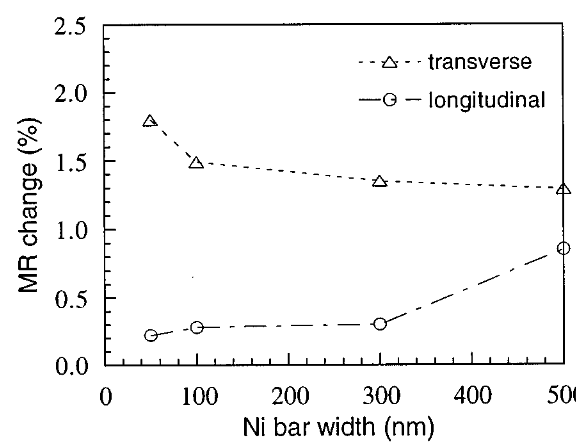

FIG. 4. Longitudinal and transverse MR changes as a function of Ni bar width.

However, the transverse MR change of Ni bars depends on the bar width. As seen in Fig. 4, the wider Ni bar has smaller transverse MR change. This is in agreement with the above discussion that the magnetization in the Ni bars is not uniform at low field. The resistance at low transverse field is reduced when the Ni bar has a portion of magnetization deviate from being parallel to the bar length. This seems unimportant in the 50 nm Ni bar as we see from Fig. 2(a) that the transverse MR change ratio equals the AMR ratio. But with the bar width increasing and the magnetization nonuniformity becoming significant, the transverse MR change ratio becomes reduced, although the AMR ratio [as obtained from Fig. 2(b)] remains as 1.8%.

The AMR ratio seems little affected by downsizing the Ni and Co bars to the nanoscale regime. Macroscale Ni and Co elements have an AMR ratio of 2.0% and 1.9%, respectively, at room temperature.[11] We see the AMR ratio of nanoscale Ni and Co bars very close to the above values. It is well known that the AMR effect is determined by the band structure of ferromagnetic metals. Electron scattering at the nanoscale bar edges may contribute to the bar resistance and then lower the AMR ratio. This seems negligible even in a bar width at 50 nm. It is also suggested that the band structure of corresponding bulk material must be retained in the nanoscale Ni and Co bars.

To confirm our observation of the width effect, we have measured Ni and Co bars of 3 μm length, i.e., with higher aspect ratio. Results are similar to that of the 1 μm length bars if the bar aspect ratio is greater than 3. For a lower aspect ratio of the bar, the current distribution across the bar width must be considered and one cannot directly obtain any longitudinal or transverse MR change.

The large jump in the MR response of the Co bars could be explained by the Barkhausen noise which happens upon a sudden and irreversible transition of magnetization state.[12] In a patterned magnetic nanostructure, the magnetization near the edge is more difficult to reverse than that in the center. Therefore, the magnetization in the center of the bar rotates first while the magnetization at the edge stays fixed. After certain rotation of the center magnetization, the magnetization at the edge suddenly snaps, reversing its direction and giving a sudden change in the MR.

In summary, we have measured the MR response of nanoscale Ni and Co bars. The width dependence of the MR behavior has been observed. The AMR ratio is determined to be about 1.8% and 1.6% for the Ni and Co bars, respectively. As the Ni bar becomes wider, the MR response is shown as due to the deviation of the magnetization direction from being parallel to the bar length. Considerable Barkhausen noise has been observed in the MR response of the Co bar of width larger than 200 nm.

Acknowledgments: The authors thank Rick C. Shi for assistance in fabrication. This work is supported by Office of Naval Research and Advanced Research Projects Agency.

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