Size effects and giant magnetoresistance in unannealed NiFe/Ag multilayer stripes

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We have observed giant magnetoresistance (GMR) in unannealed NiFe/Ag multilayer thin-film stripes. Rectangular stripes having constant thickness and a constant 11:1 length-to-width aspect ratio, but varying widths down to 0.5 μm, were measured. Two types of multilayer configurations were tested, a system of five NiFe/Ag bilayers with 5.5-nm-thick Ag spacer layers, and a system of nine bilayers with 4.4-nm-thick Ag layers. In contrast to the characteristic of annealed NiFe/Ag multilayer stripes, the unannealed stripes produced increasing GMR ratios for decreasing stripe sizes, with the 0.5-μm-wide stripe of the five-bilayer system exhibiting a $\Delta R/R$ of 2.5%. Barkhausen noise and response broadening also increased with decreasing stripe size, however. The results are discussed in terms of magnetostatic coupling of the NiFe layers within the stripes.
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INTRODUCTION

Studying finite-size effects in giant magnetoresistive (GMR) materials is important both for understanding the micromagnetic phenomena as well as for examining suitability for magnetic sensor applications. The multilayer NiFe/Ag GMR system[1–7] is attractive for potential sensor applications due to its high sensitivity (large change in MR per unit field), especially when annealed to form discontinuous multilayers.[2] In this form, the magnetic NiFe layers are broken up into small grains due to Ag diffusion along grain boundaries.[4] These grains interact magnetostatically to induce antiferromagnetic ordering among neighboring grains in adjacent NiFe layers at low fields. The relatively high degree of antiparallel alignment gives rise to GMR values on the order of 5%. When these annealed multilayers are patterned into micrometer-scale features, however, the magnetoresistive response is significantly suppressed, broadened, and characterized by the presence of distinct ''jumps'' (Barkhausen noise).[8,9] These characateristics are unsuitable for submicrometer sensor applications.

Recently, GMR in patterned unannealed NiFe/Ag multilayers was reported.[10] The unannealed NiFe/Ag is potentially more attractive for applications since the annealing step is avoided. It may also decrease the noise previously observed in small devices,[8,9,11] if the granular characteristics are eliminated. Hylton *et al.*[10] studied unannealed arrays of 2 μm dots consisting of two NiFe layers separated by a Ag spacer. MR measurements carried out on the dot arrays, corrected for the continuous Cr overcoat necessary for electrical contact, gave estimated GMR ratios of 2.5% and a 1.6 kA/m (20 Oe) saturation field. The GMR effect was attributed to magnetostatic coupling induced at the edge of the dots, which causes the magnetization in one layer to align antiparallel to the other layer.

In this study we have patterned unannealed NiFe/Ag multilayers into rectangular stripes of various sizes to examine the role of magnetostatics in unannealed NiFe/Ag multilayers. In particular, the goal was to directly test whether individual stripes having widths on a 1 μm scale could have interlayer magnetostatic coupling sufficiently large to produce GMR, and, if so, whether their MR response contained less noise than their annealed counterparts. Stripes fabricated from five- and nine-bilayer systems both showed increasing GMR amplitude as the stripe width decreased from 16 μm. In both cases, however, saturation fields and noise also increased with decreasing stripe width.

EXPERIMENT

NiFe/Ag multilayer films were fabricated by magnetron sputtering onto SiO_2-coated Si wafers as reported previously.[6] The films were deposited at room temperature in 0.93 Pa (7 mTorr) of Ar, and no magnetic field was applied during the deposition. NiFe was sputtered from a $Ni_{82}Fe_{18}$ alloy target. Two wafers with varying bilayer number n and Ag thickness t_{Ag} were used: Si/SiO_2 (150 nm)/Ta (4.5 nm)/Ag(t_{Ag}/2)/NiFe(2.0 nm)/[Ag (t_{Ag})/NiFe(2 nm)]$_{n-1}$/Ag (t_{Ag}/2)/Ta(11 nm), with $n=5$, $t_{Ag}=5.5$ nm, and $n=9$, $t_{Ag}=4.4$ nm. After deposition the central regions of the wafers were patterned using conventional photolithography and diced into 12.5×12.5 mm^2 chips. Several of the chips were annealed in a rapid thermal annealing furnace for 5 min in a 5% H_2–Ar ambient. These chips were used for direct comparison with the unannealed chips. Rectangular stripes having nominally 11:1 length-to-width aspect ratios were measured at room temperature using a two-probe MR tester. The active areas defined by the Au contact electrodes were one square. Bias currents were scaled approximately with stripe width, with current density $J\sim5\times10^5$ A/cm^2, and the magnetic field was applied in the plane of the stripe. For cross-sectional transmission electron microscopy (TEM) studies, specimens were prepared using standard techniques, including N_2-cooled ion milling. Care was taken to prevent heating in excess of 70 °C during all TEM sample preparation steps.

RESULTS

The central result of this article is illustrated in Fig. 1. Figure 1(a) shows $\Delta R/R$ as a function of applied field for unannealed NiFe/Ag rectangular stripes having $n=5$ and

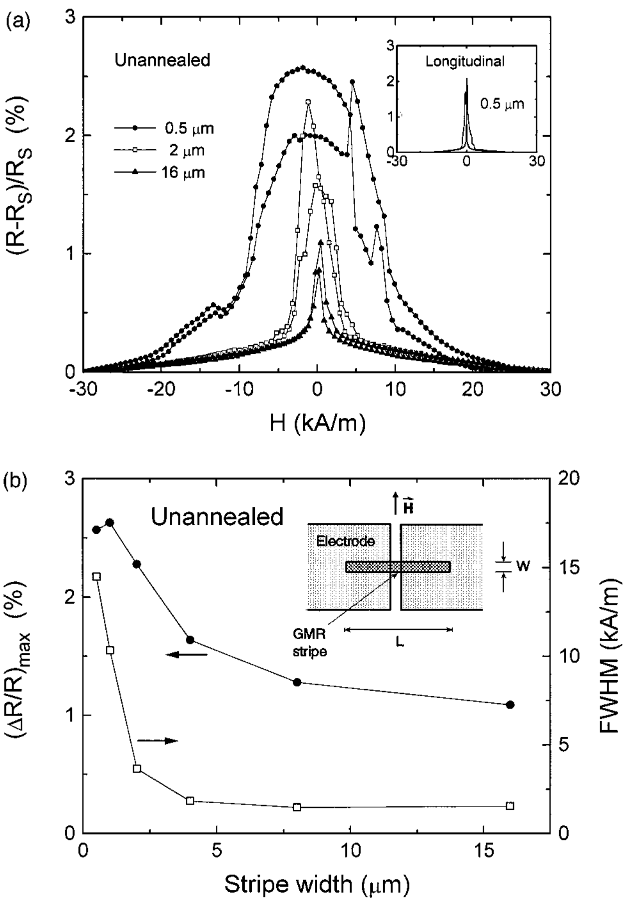

FIG. 1. (a) Magnetoresistive response for unannealed NiFe/Ag multilayer (n=5,t_{Ag}=5.5 nm) stripes. The field was applied in the plane of the stripe and transverse to the long direction. Inset: longitudinal MR for the 0.5-μm-wide stripe. (b) Maximum $\Delta R/R$ and full width at half-maximum data for various stripe widths. Inset: schematic of transverse MR measurement.

t_{Ag}=5.5 nm. The stripes have nominal widths ranging from 0.5 to 16 μm. As the stripe width W decreases, the MR response increases in amplitude and broadens. This is seen more clearly in Fig.1(b), where the maximum $\Delta R/R$ and full width at half-maximum (FWHM) data are plotted as functions of W. As W decreases from 16 to 0.5 μm, maximum $\Delta R/R$ increases from 1.1% to 2.6%, and the FWHM increases from 1.6 to 14 kA/m (20 to 180 Oe). The sensitivity $[d(\Delta R/R)/dH]_{max}$ therefore decreases with decreasing W. The inset of Fig. 1(a) shows $\Delta R/R$ for the 0.5 mm stripe with longitudinal applied field. Although the longitudinal results show trends similar to the transverse results, the magnitude of the longitudinal broadening is much less (1.2 kA/m as opposed to 14 kA/m for the 0.5 μm stripe).

We also measured the MR response for unannealed stripes having n=9 and t_{Ag}=4.4 nm. As in the case of the five-bilayer stripes of Fig. 1, the nine-bilayer samples show the trend of increasing $\Delta R/R$ and broadening with decreasing W. For these stripes, the maximum $\Delta R/R$ increases from 0.4% to 1.9% as W decreases from 16 to 2 μm. The trends that we observe are, therefore, independent of n and t_{Ag} within these ranges.

Noise, in the form of discrete Barkhausen jumps in the MR response, is readily apparent for the smaller stripes in

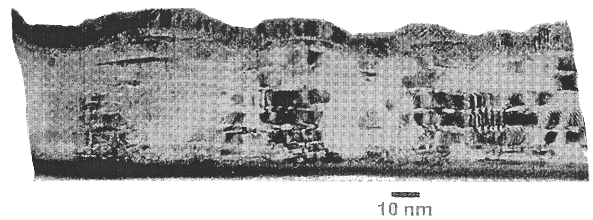

FIG. 2. Cross-sectional TEM micrograph of an unannealed seven-bilayer sample. The GMR multilayer is sandwiched between top and bottom Ta layers. The degree of roughness at the top surface (~5 nm) is typical of the several samples examined.

Fig. 1(a). This may be attributed to a finite granularity (imperfect multilayers), which also produces a nonzero GMR in the larger devices. TEM results on different wafers show a roughening in the unannealed films on the order of a bilayer thickness, as shown in Fig. 2. Previous work has indicated the significance of sputtering gas pressure on film microstructure and properties.[33] The relatively high Ar pressure used during sputtering in this study may introduce some of the observed roughness. Temperatures up to 130 °C are used during photolithography, but these low processing temperatures are not likely to account for the residual granularity and presence of a small GMR component in the larger unannealed stripes. The Barkhausen noise observed in the response of the small stripes is discouraging for sensor applications. However, processing optimization or biasing optimization, such as increased current density,[9] may diminish the noise problem.

The trend of increasing $\Delta R/R$ with decreasing W for these unannealed stripes is in contrast to annealed stripes. Annealed stripes exhibit decreasing $\Delta R/R$ with decreasing W, as illustrated in Fig. 3 for the n=5,t_{Ag}=5.5 nm configuration (from the same wafer as the unannealed n=5 chip) annealed at 340 °C for 5 min in 5% H_2–Ar. The maximum $\Delta R/R$ decreases from 3.6% to 3.0% as stripe width decreases from 16 to 0.5 μm.

DISCUSSION

In the unannealed stripes, the trend of increasing $\Delta R/R$ with decreasing W is due to the increased thickness-to-volume ratio as W decreases (thickness is constant), and, therefore, the increased relative influence of the stripe edges perpendicular to the layers. As W (and L) decreases, the magnetostatic edge charges become closer. If the layers are fully continuous (not granular), the magnitude of magnetostatic energy per unit volume should be greater for the smaller stripes, leading to increased antiparallel alignment in zero applied field, and a larger maximum $\Delta R/R$. In this case, a larger field is required to overcome the magnetostatic energy and align the layers, leading to a broadened response.

The annealed stripes, in contrast, consist of discontinuous layers, so the increasingly strong effect of the stripe edge charges, with decreasing size, increasingly dominates the intergranular, interlayer magnetostatic interaction that occurs

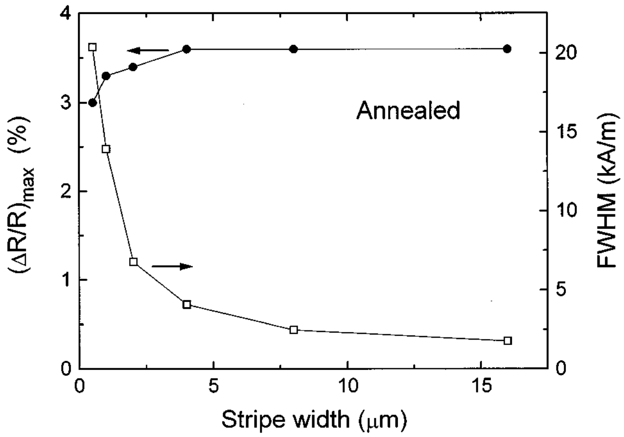

FIG. 3. Maximum $\Delta R/R$ and full width at half-maximum data for various stripe widths in a series of annealed NiFe/Ag stripes having $n=5$ and $t_{Ag}=5.5$ nm. The annealing was carried out in a rapid thermal annealer for 5 min at 340 °C.

due to charges at the grain edges. Some of the zero-field antiparallel orientation is diminished, reducing the maximum $\Delta R/R$ as W decreases.

The increased Barkhausen noise for the smaller samples is attributed to the increased relative contribution of flipping of domains as the domain size becomes an appreciable fraction of the stripe size.

SUMMARY

We have observed increasing GMR amplitudes with decreasing size in rectangular stripes of unannealed NiFe/AG multilayers. This may be attributed to an increasing significance of magnetostatic charges at the stripe edges as film thickness-to-volume ratio increases, given a constant length-to-width ratio. Noise and response width also increase with decreasing stripe size, however, posing a challenge for technological applications such as highly field-sensitive submicrometer magnetic sensors.

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