AIP | Journal of Applied Physics

In situ applied field imaging of a magnetic tunnel junction using magnetic force microscopy

J. Leib, C. C. H. Lo, J. E. Snyder, and D. C. Jiles

Citation: J. Appl. Phys. 93, 8537 (2003); doi: 10.1063/1.1540128
View online: http://dx.doi.org/10.1063/1.1540128
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v93/i10
Published by the American Institute of Physics.

In situ applied field imaging of a magnetic tunnel junction using magnetic force microscopy

J. Leib[a)]
Department of Materials Science and Engineering, Iowa State University, Ames, Iowa 50011 and Ames Laboratory, U.S. Department of Energy, Ames, Iowa 50011

C. C. H. Lo
Ames Laboratory, U.S. Department of Energy, Ames, Iowa 50011

J. E. Snyder and D. C. Jiles
Department of Materials Science and Engineering, Iowa State University, Ames, Iowa 50011 and Ames Laboratory, U.S. Department of Energy, Ames, Iowa 50011

(Presented on 15 November 2002)

Knowledge of domain behavior in magnetic tunnel junctions is an essential component, together with knowledge of the electron band structure, for understanding their magnetoelectronic properties. To this purpose, the magnetization reversal processes of a multilayer tunnel junction of structure substrate/NiFe/AlO_x/FeCo/CrPtMn/Al of tapered half-ellipsoid shape have been imaged using a magnetic force microscope (MFM) with *in situ* applied magnetic fields. Stripe domains through both the stack and free layers observed at zero applied field were erased by a ~100 Oe field applied to the left followed by applying a small field to the right. Magnetic domain structure did not reappear in the MFM images until a field of ~400 Oe was applied to the right. This domain pattern then persisted when the magnetic field was reduced to zero. A drastic difference in domain patterns throughout the rotational processes to saturation in each direction was also observed. When the field was applied to the left, domain walls rotated toward the direction perpendicular to the applied field before disappearing. However, in near-saturation fields to the right, domain walls formed nearly parallel to the applied field and rotated away from parallel as the applied field strength was decreased. From these images, therefore, significant insight has been gained into the magnetization processes and physical phenomena behind the magnetoresistive behavior of these junctions.
 [DOI: 10.1063/1.1540128]

I. INTRODUCTION

Magnetic tunnel junctions (MTJ's) that show magnetoresistance at room temperature were first observed in 1995 by Moodera and co-workers,[1] and fabricated by photolithographical techniques at NonVolatile Electronics in 1996.[2] MTJ's are a topic of great current scientific and engineering interest.[3] The phenomena involved and the potential applications are both of significant interest. MTJ's pass a tunneling current from one ferromagnetic electrode through an insulating layer into a second ferromagnetic electrode, and this current depends on spin-dependent tunneling. The resistance of the junction depends on the relative directions of the magnetization in the two ferromagnetic electrodes as well as on the occupancy of majority and minority spin half bands. The magnetoresistive response of MTJ's depends on switching of the magnetization of the magnetic layers under an externally applied field, the details of which even now have not been fully addressed. The aim of this work is to investigate the magnetization reversal processes in MTJ's through direct observation of the domain wall processes using magnetic force microscopy (MFM) with *in situ* applied field capability.

[a)]Electronic mail: jleib@iastate.edu

II. EXPERIMENTAL METHODS

The MTJ's with a multilayer structure consisting of substrate / NiFe (120)-AlO_x(15)-FeCo(54)-CrPtMn(328) -Al(54) (Fig. 1, all dimensions in angstroms) were deposited at NonVolatile Electronics on a Si wafer and patterned into a variety of devices for investigation. The junction studied was chosen for its large size (to ease MFM imaging) and its relatively large distance from other magnetic structures on the wafer (to reduce unwanted interactions and interference). It was patterned into a tapered half-ellipsoidal shape with dimensions of ~12 μm at the widest point along the short axis and ~40 μm along the long axis, with the bottom NiFe free layer a full ellipsoid. A magnetic anisotropy was induced in the NiFe layers, with the easy direction of magnetization along the short axis of the ellipsoid. A magnetic force microscope (Digital Instruments, Inc., Dimension 3100) was used in this research, employing magnetic probes (Digital Instruments, Inc., MESP) coated with CoCr. The MFM was equipped with an electromagnetic stage capable of applying variable magnetic fields up to ±600 Oe to the junction *in situ* in the sample plane. The applied field was monitored using a Hall probe embedded in the magnetizing stage. Images were taken at several constant applied fields over three-quarters of a typical hysteresis loop starting with an initial magnetiza-

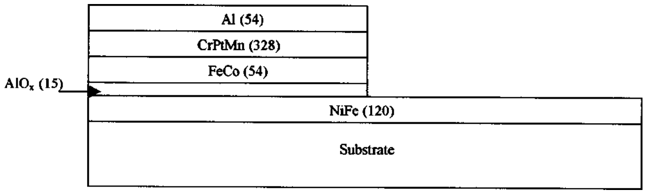

FIG. 1. Schematic diagram showing the multilayered structure of the magnetic tunnel junction sample (dimensions shown in angstroms).

tion curve (zero field to high negative field to high positive field to remanence, positive being to the right of the image).

III. RESULTS AND DISCUSSION

Magnetic images of the junction when subjected to various applied fields are shown in Fig. 2 for fields applied to the left and in Fig. 3 for fields applied to the right. The junction stack is shown in the left half of each image, with the stack boundary oriented vertically down the center and the tapered tip beyond the top edge of the scan. The area to the right of the stack was the NiFe free layer electrode with its easy axis horizontal to the images, or perpendicular to the long axis of the junction multilayer.

The as-received state of the sample, as shown in Fig. 2, exhibited wide stripe domains with walls that extend straight past the stack boundary and through the NiFe electrode, with a spatial periodicity of $\sim$2.75 μm. Narrow, dark contrast lines repeating over the same period were also present and extended across the physical boundary. The continuity of domains was a recurring trend throughout the image series (even after the dark lines reappeared in Fig. 3), but the stripes did not reemerge after fading, shown in the last images of both Figs. 2 and 3. These stripes were thus not likely to correspond to an equilibrium domain pattern, but more likely are an artifact of the deposition and exchange bias and magnetic easy axis processing.

The observed domain rotation and its differing behavior in opposite field directions was most unusual. As seen in Fig. 2, when the magnetic field vector pointed to the left, increasing applied field strength resulted in a rotation of domain patterns toward the vertical axis. Increasing the field strength beyond 100 Oe did not perceptibly change the image, so the field was then reduced back toward zero. As the field was reduced, the rotation toward the vertical axis resumed, finishing at or near perpendicular to the field direction at remanence. As the field was then increased to the right (Fig. 3), all domain patterning disappeared entirely, indicating a reduction in the vertical (z) component of the magnetic moment to zero. This change is possibly due to an antiparallel moment arrangement in the pinned and free layers, providing a more energetically favorable closed flux path within the x-z plane of the sample. This lack of image contrast persisted until a field strength of 400 Oe was applied, where the same line patterns as observed before reappeared toward the tip of the ellipse. Unlike the pattern under the highest field toward the left, these lines were almost horizontal and rotated back away as the field was decreased. If the initial and final images are examined, the spacing and angle of the narrow, dark lines are found to be the same. The nominal exchange bias field at the pinned layer is 300 Oe, so the magnetization processes with the field applied to the right would appear to involve reversing magnetization at the pinned layer against its bias field, while those with the field applied to the left would be along predominantly the exchange bias field.

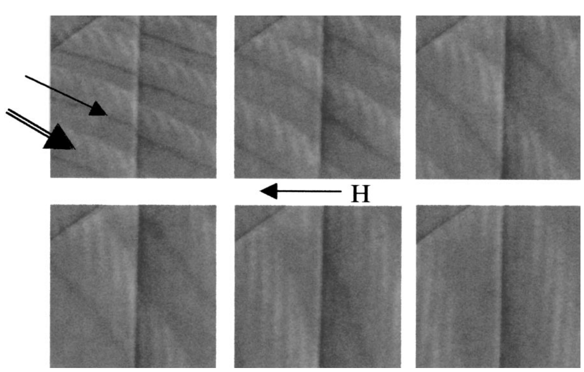

FIG. 2. 9.4-μm-square magnetic force microscopy images of domain configurations with junction multilayer on the left and NiFe electrode on the right. Field strengths are, from left to right and top to bottom, 0, 40, 70, 100, 40, and a return to 0 Oe, in chronological order. The arrows with single and double lines indicate the dark lines and stripe domains, respectively. Junction multilayer dimensions are $\sim$12 μm in the **x** direction (short axis) at their widest point and $\sim$40 μm in the **y** direction (long axis).

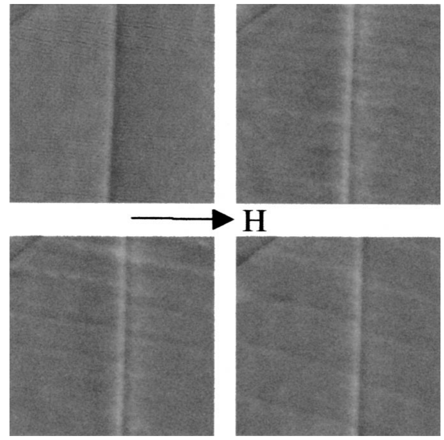

FIG. 3. Magnetic force images of junction and electrode at, from left to right and top to bottom, 100, 400, 200, and a return to 0 Oe. Images are also in chronological order.

It is clear that the observed changes in domain pattern in this magnetic tunnel junction in response to the applied field involved a complex interaction between layer biasing, electrode easy axis, shape anisotropy of each electrode, magnetostatic interaction of the electrodes, and antiferromagnetic exchange biasing of the pinned layer. Domains are apparent in regions of the hysteresis loop where by a simple picture one would expect the pinned layer and free layer to be magnetized in the same direction. A full explanation of the differences in behavior in different applied field directions will require simultaneous measurement of both magnetoresistance and domain structure, an experiment that will be conducted subsequently. However, the interaction between the CoFe pinning and NiFe electrode layers was very clear, with magnetic domain structures continuing across the physical edge of the junction. An antiferromagnetically coupled second CoFe layer beneath the first would likely eliminate this domain interaction by completing a closed flux path of the CoFe layers.

IV. CONCLUSIONS

Domain structures of a magnetic tunnel junction under *in situ* applied fields have been imaged using a magnetic force microscope. Coupling of the CoFe layer in the multilayer and the NiFe electrode free layer was readily observed, as was a complex domain rotation mechanism that was dependent on many factors. These factors, including field direction, stray field from the pinned CoFe layer, anisotropy of the NiFe free layer, shape anisotropy, and magnetostatic interaction between the magnetic layers, must therefore all be included in any valid theoretical model of magnetic devices based on these types of magnetic tunnel junctions.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation, Division of Electrical and Communications Systems under Grant No. ECS-0100799. The authors are grateful to NonVolatile Electronics, Inc. for providing the magnetic tunnel junction sample.

[1] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995).
[2] R. S. Beech, J. Anderson, J. Daughton, B. A. Everitt, and D. Wang, IEEE Trans. Magn. **32**, 4713 (1996).
[3] J. S. Moodera and G. Mathon, J. Magn. Magn. Mater. **200**, 248 (1999).