

## The development of information storage materials – How microscopy can help?

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**Abstract.** The response of giant magnetoresistance (GMR) devices depends critically on the film microstructure, with parameters such as layer thickness and interfacial abruptness being crucial. This paper presents results obtained using high resolution electron microscopy (HREM), chemical mapping and atom probe microanalysis. Local variations in the magnetic properties are induced by the microstructure and also when the films are patterned to form small elements. These lead to changes in the magnetization reversal mechanism. Some results of the studies of the magnetization reversal carried out using *in situ* in Lorentz transmission electron microscopy (LTEM) magnetizing experiments are also included.

**Keywords.** Information storage materials; high resolution transmission electron microscopy; magnetic domains; atom probe analysis.

**PACS Nos** 68.37.Lp; 75.60.Jk

### 1. Introduction

Over the past few years, there has been an increased effort in the development of new materials for information storage applications, often in the form of layered structures containing many thin layers. The structures that are being most widely developed for read-heads, which currently limit the achievable storage density, rely on the giant magnetoresistance (GMR) effect, namely spin-valve (SV) structures or spin-dependent tunnel junctions (STJs) [1,2]. Similar structures are also being developed for magnetoresistive random access memories (MRAM) [3,4] to go beyond the limits on memory density that can be achieved using solid-state memory.

Interest has focused on SV materials [5] which make use of the GMR effect (a large change in resistance in an applied magnetic field), as they provide many more possibilities for development for real applications. The change in resistance results from a change in the relative orientation of the magnetization in the ferromagnetic (F) layers – parallel magnetization in adjacent layers (P configuration) gives a low resistance, whereas a high resistance is measured if the magnetization in adjacent layers is antiparallel (AP configuration). SV

structures consist of two F layers separated by a non-magnetic layer (spacer layer). The magnetization direction of one FM layer is fixed by an adjacent antiferromagnetic (AF) layer (pinning layer) through exchange coupling. The magnetization direction of the other FM layer (sense layer) can be rotated by applying a low external magnetic field. STJ films differ from SV films only in that the non-magnetic spacer layer is an insulator, and the current is passed normal to the layers. Two main configurations are widely used for applications: (a) applying the external field perpendicular to the easy axis, giving a linear change in resistance with low coercivity and a sense layer magnetization reversal characterized by coherent rotation (suitable for sensors); (b) applying the external field along the easy axis direction, resulting in two remanent states with either P or AP alignment of the magnetizations of the pinned and sense layers. The reversal is then a hysteretic process, with the P and AP states corresponding to the minimum and maximum resistance values respectively (suitable for MRAM devices).

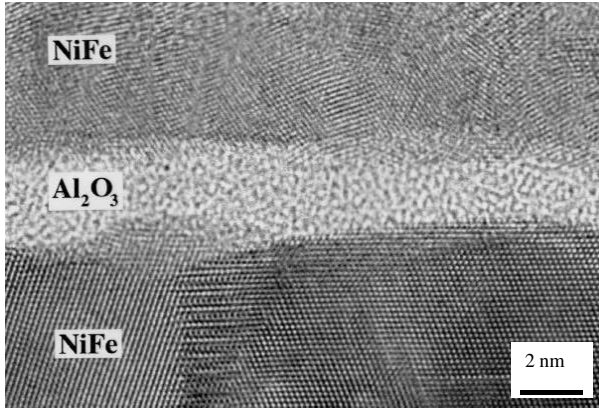
There are a number of problems remaining to be solved for both SV and STJ structures, which require understanding the microstructure and local magnetic structure of the films and devices at high spatial resolution. Electron microscopy and three-dimensional atom probe (3DAP) microscopy are ideally suited to this study, and this paper gives examples of the applications of these techniques to microstructural analysis, using high resolution electron microscopy (HREM), magnetic domain structure and magnetization reversal studies, using Lorentz microscopy, and composition mapping, using 3DAP.

## **2. Experimental details**

All the films discussed in this paper were grown by sputter deposition, which produces a polycrystalline film. This technique is used because it is relatively simple and less expensive to implement, but the fact that the films are polycrystalline makes their characterization more complex than for single crystal films. Samples were prepared either in cross-section for HREM, or in plan-view for Lorentz microscopy. Samples for 3DAP were prepared by depositing the films on the end of Si posts and using a focused ion-beam to produce sharp needles with an end radius of the order of 50 nm [6].

## **3. Results and discussion**

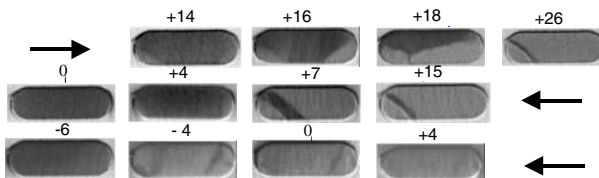
Figure 1 shows an HREM image of an STJ structure in which the various layers are clearly visible. The HREM analysis was carried out using a JEOL 4000EX operated at 400 kV (point-to-point resolution 0.16 nm). The NiFe FM layer and the FeMn AFM layer below the amorphous aluminium oxide tunnel barrier are polycrystalline with a strong (111) crystallographic texture induced by a Ta seed layer. However, the NiFe layer deposited on the amorphous barrier shows a more random structure with smaller grains. This results in somewhat different magnetic properties for the two FM layers. An additional feature is the waviness of the lower surface of the amorphous barrier, caused by the columnar grain growth in the underlying layers. The shape of this interface is critical because the tunneling current drops off exponentially with increasing barrier width. A quantitative image analysis technique, originally developed for studying semiconductor interfaces, can be applied to the analysis of interface position, sharpness and flatness in SV materials, in which



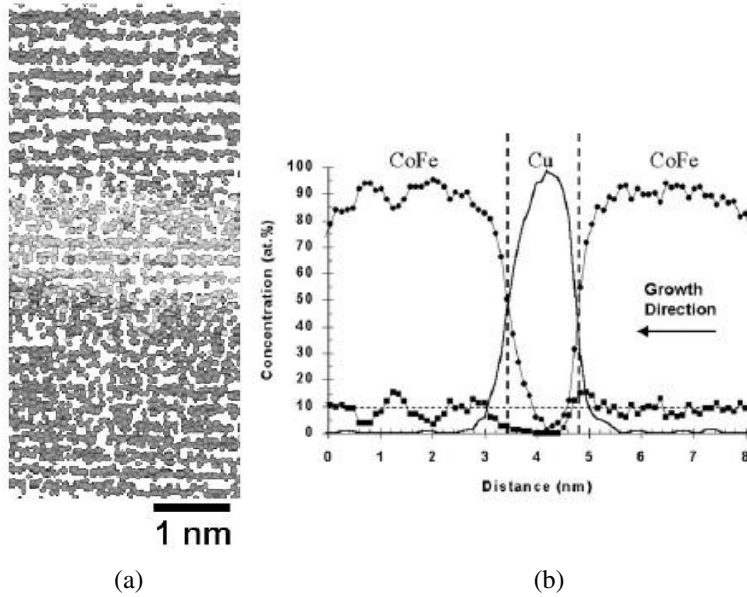
**Figure 1.** Cross-section HREM image of a MnFe/NiFe/Al<sub>2</sub>O<sub>3</sub>/NiFe spin tunnel junction structure showing the FM and barrier layers.

the interfaces are not always clearly visible because all of the layers tend to be of similar atomic number [7]. The degree of interfacial waviness, which can lead to FM magnetostatic coupling between the pinned and sense layers, has been analyzed using this technique [8].

The GMR effect relies on the change in magnetization direction in the FM layers, and thus on the local magnetic domain structure and magnetization reversal mechanism. One of the techniques enabling micromagnetic studies at the sub-micron scale is Lorentz transmission electron microscopy (LTEM). A detailed description of the interpretation of domain images and of the origins and theory of magnetic domains is given in [9]. Figure 2 shows LTEM Foucault mode images of the magnetization reversal of the sense layer in a Ta/NiFe/MnFe/NiFe/Al<sub>2</sub>O<sub>3</sub>/NiFe/Ta (5/6/10/4/2.5/7/5 nm) STJ element (width 2 μm). The arrows indicate the direction of the applied field and the numbers indicate the value of the magnetic field (Oe) applied *in situ* in the LTEM. After applying a positive field, a 360° domain wall is formed by the combination of two 180° domain walls (imaged as adjacent bright and dark lines). The wall is pinned at a structural defect at the element surface. The field was then increased to +60 Oe and decreased (centre row of images). The 360° wall defect acted as a domain nucleation site. If the magnetization cycle was then repeated but with the positive field increased to +80 Oe, the 360° wall was removed and reversal of the sense layer magnetization occurred at a higher negative field. This experiment shows the problems involved in producing large arrays of STJ elements for memory



**Figure 2.** LTEM images showing *in situ* magnetization reversal of the sense layer in a MnFe/NiFe/Al<sub>2</sub>O<sub>3</sub>/NiFe STJ element (width 2 μm).



**Figure 3.** 3DAP data from CoFe/Cu multilayer sample. (a) Atom map and (b) composition profile.

applications, in which the magnetization reversal field of all the element must be the same. Further developments are to heat or cool the specimen (with or without an external applied field) and to apply a current *in situ* in the LTEM.

3DAP analysis provides a technique for analyzing the composition in three dimensions [10]. 3DAP data across a  $\text{Co}_{90}\text{Fe}_{10}/\text{Cu}/\text{Co}_{90}\text{Fe}_{10}$  section of a multilayer stack is shown in figure 3a. There is strong (111) texture along the film normal, and the individual atomic planes are visible across much of the image. A corresponding composition–depth profile is shown in figure 3b. The centre of the Cu layer contains  $4.4 \pm 1.2\%$  Co, and in the CoFe layers, the average composition is Co- $8.9 \pm 0.7\%$  Fe. There is an asymmetry in the interfaces on either side of the Cu layer: the widths are different, with 10–90% values measured to be  $0.82 \pm 0.10$  nm ( $\sim 4$  atomic planes) for CoFe-on-Cu, but only  $0.47 \pm 0.15$  nm ( $\sim 2$  atomic planes) for Cu-on-CoFe. The 3DAP data also show that the CoFe-on-Cu interfaces are flatter than the Cu-on-CoFe interfaces, i.e., Cu acts to smoothen the surface of the growing multilayer film [11]. This had been proposed in a model to explain magnetotransport effects in CoFe/Cu multilayers [12], but had not previously been seen experimentally. Recently, molecular dynamics modeling of the growth process has confirmed the existence of the asymmetry in the CoFe/Cu interfaces [13] seen in the 3DAP data.

#### 4. Conclusion

In summary, the use of electron microscopy has enabled a considerable amount of information about the microstructure, composition distribution, magnetization reversal mechanism

and transport properties in SV and STJ structures to be determined. As the structures and devices become smaller and more complex, the need to analyze them at high spatial resolution will continue to be of great importance.

### **Acknowledgements**

The studies described above were part of collaborative projects with Hewlett-Packard Labs and Seagate Technology. We are grateful to the EPSRC for financial support, to Prof G D W Smith for laboratory space and the AIP for permission to publish figure 3.

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