MATERIAL CONSIDERATIONS AND FABRICATION METHODS FOR RAPID PROTOTYPING OF MTJS

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Abstract. Recently, the use of magnetic tunnel junctions (MTJ) in hard drive read heads, magnetic random access memory (MRAM), and sensor applications has increased strongly. The physical etching commonly employed for the patterning usually leaves material residues causing deterioration of the MTJ devices. Here, therefore, two rapid prototyping methods: focused ion beam (FIB), and ion milling in an equipment for electron spectroscopy for chemical analysis (ESCA), are proposed and investigated with particular emphasis on material and processing considerations. The experiments were conducted on a TMR stack of: Ru/Ta/Co60Fe20B20/Mg/MgO/Co60Fe20B20/ Ru/Co70Fe30/PtMn/Ta/CuN/Ta. Advantages and drawbacks of both methods are discussed in terms of speed, accuracy, quality and flexibility. Being so crucial for the performance of the MTJs, the possibility to terminate the etching at the 1.1 nm thick barrier layer by using ESCA to monitor the composition with depth is investigated in particular. For iteration of the MTJ design and manufacturing, as normally needed in research, the ESCA method is concluded superior.
Từ khóa (Keywords): MTJ, TMR, rapid prototyping, Gallium implantation

INTRODUCTION

The use of magnetic tunnel junctions (MTJ) made from tunnelling magnetoresistance (TMR) stacks in hard drive read head [1] and magnetic random access memory (MRAM) [2] has increased strongly in the last decade. Magnetic coupling in the stack's layers, which are deposited with better than nanometre accuracy in thickness [3], and patterned laterally with sub-micrometre precision, determines the performance and packing density of the MTJs in a device. The physical etching commonly employed for patterning, usually leaves material residues causing deterioration of the MTJ devices to various extents. The optimized process used for large-scale production differs considerable from the rapid prototyping typically asked for in research. In this paper, two rapid prototyping methods using FIB and ESCA equipment, respectively, are proposed and investigated with particular emphasis on material considerations.

EXPERIMENTAL

The experiments presented here, as a part of the project Spin Dependent Tunneling Magnetometer for space at The Ångström Space Technology Centre at Uppsala University, Sweden, were conducted on a TMR stack of: 7Ru/10Ta/3$Co_{60}Fe_{20}B_{20}$/0.3Mg/1.1MgO/3$Co_{60}Fe_{20}B_{20}$/0.8Ru/2.5$Co_{70}Fe_{30}$/20PtMn/5Ta/30CuN/5Ta, where the capital numbers are thicknesses in nm, and subscripts are contents in atom %.

Rapid prototyping of MTJ using FIB. Usually, a FIB system contains different units for physical etching and deposition using an ion beam, or an electron beam, as well as units for *in-situ* analysis and monitoring using, e.g., scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). FIB is serial, and hence slow, in its processing, but offers great versatility and high resolution. The MTJ prototypes described here were fabricated with a FIB equipment in one run with all steps *in-situ*.

At first, a spot on a sample from the TMR stack was arbitrarily chosen and etched all the way through to get a so called end point detection (EPD) profile, Fig. 1. With the so obtained good knowledge and depth resolution of the TMR stack, the actual patterning could then be accurately performed on the same sample, and permitting, e.g., a precise etch stop at the stack's bottom electrode layer.

Figure 2 below contains the scheme used to fabricate the MTJs in the FIB equipment. The etch and deposition rate of the FIB depends on the beam current. Thus, a high beam current can be used to reduce the fabrication time, but with reduced pattern resolution. Referring to Fig. 2, the patterning and capping steps (c, d and f) employed a low beam current giving high pattern resolution, whereas the patterning step (e) for making larger bottom contacts employed a high beam current giving a higher etch rate, but a lower,

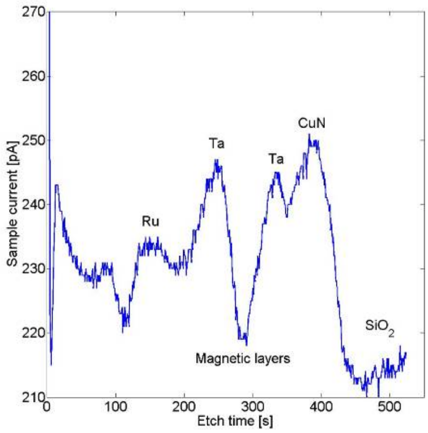

Fig. 1. *End point detection profile of the TMR used as reference in the MTJ patterning process using FIB.*

yet acceptable, resolution. The alignment mark shown in step (b) was used to align the high and low resolution patterns to each other. The capping and deposition steps (d and f, respectively) were performed using ion-assisted chemical vapour deposition (IACVD) of SiO_2. The contact wires (step g) were made of Pt, using a combination of electron- and ion-assisted CVD, in order to avoid Ga implantation directly into the whole MTJ. All patterns used for milling and coating inside the FIB were generated from bitmap images and simply imported to the FIB software. By this, the total process time from design to a fabricated MTJ, including the contacts, could be as short as 1.5 h.

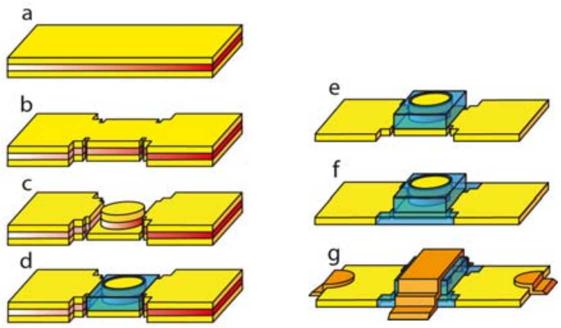

Fig. 2. *Scheme of the FIB-based MTJ manufacturing process.*

Rapid prototyping of MTJ using ESCA. ESCA systems are mainly intended for chemical analysis of material. Since material of the sample can be removed with a close to atomic depth resolution using argon ion milling, the equipment can be used for patterning of MTJs according to the following.

A separate sample was used to obtain a composition depth profile, Fig. 3, by careful sputtering and analysis in steps alternating through the stack. With this as a reference, quick etching can be made to the vicinity of the layer targeted.

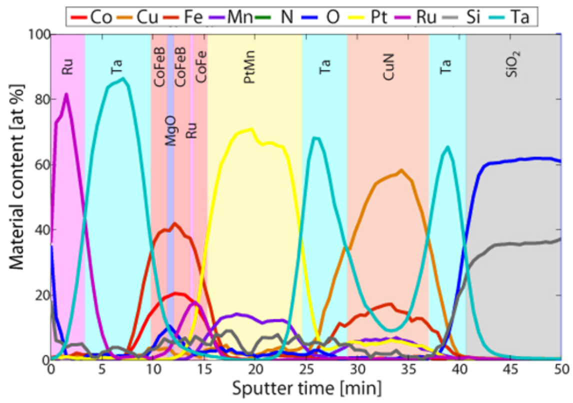

Fig. 3. *Depth profile for etching in ESCA..*

The next sample could then be patterned into MTJs based on the depth profile obtained. The ion milling in the ESCA was preceded by UV lithography-based masking into features with lateral sizes of 10-100 µm. The mask endured until the antiferromagnetic PtMn layer was reached. At this point the ESCA processing was terminated. The next step was to cap the ion milled patterns by lift-off of reactively sputtered SiO_2, and, finally, deposit contact wires using lift-off of sputtered Al, according to the process scheme shown in Fig. 4. The effective time needed to fabricate an area of 4x4 mm containing 36 MTJs was about 5.5 hour. However, since the fabrication involves many pieces of equipment, requiring separate preparation and clean up, the actual manufacturing time is probably a couple of days.

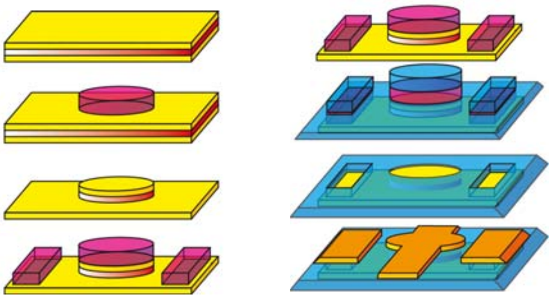

Fig. 4. *Scheme of the MTJ fabrication process using ESCA equipment.*

Evaluation. The tunnelling magnetoresistance (TMR) of the MTJs from both processes were evaluated using a four point probe, measuring their resistance as a function of ambient magnetic field. The magnetic field was applied using a standard electromagnet and was oscillated with a triangular waveform having an amplitude of 25-50 mT and a period of 30 minutes. The measurements were conducted at room temperature and the magnetic field was aligned to both the easy and hard axes of the samples. The processes were also monitored *in-* and *ex-situ* using SEM and EPD in the FIB and photoelectron spectroscopy in the ESCA as well as atomic force microscopy (AFM) for measuring the etch depths and coating thicknesses.

RESULTS

The MTJs from the FIB process were studied with AFM, and successful fabrication of elliptic MTJs with minor and major axis of roughly 1 and 2 micrometers, respectively, were verified.

As seen in Fig. 5, the TMR curves of the MTJs from the FIB process (top row) exhibit a jump giving a deteriorated linearity for the hard magnetic axis (top-right) and a hysteresis for the easy magnetic axis (top-right), whereas these phenomena were absent for the case of the MTJs from the ESCA process (bottom row).

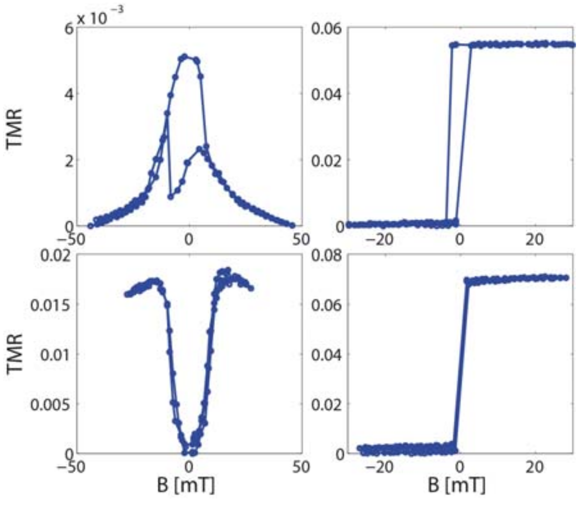

Fig. 5. *TMR measurements of the MTJs from the FIB process (top row), and from the ESCA process (bottom row). The magnetic field was applied both along the hard axis (left column) and the easy axis (right column).*

DISCUSSION AND CONCLUSION

The results in Fig. 5 shows that the FIB process caused increased coercivity and deteriorated linearity in the MTJs. These effects might be related to the Ga implantation [4] in the TMR layers of the MTJs. The reason is that, although being focused, the ion beam still has a Gaussian distribution. Thus, on milling the contours of the MTJs, a belt is created where the content of Ga is higher. The deteriorated magnetic coupling between the belt and the inner part of the MTJs might be the cause of the phenomena mentioned here. So far, this, rather than the beam width, appears to set the miniaturization limit when FIB is used to manufacture MTJs.

Although in the FIB process, the etch depth can be monitored *in-situ* using EDP, its coarse resolution does not facilitate a very precise etch stop. Probably, an etch stop at the MgO barrier of 11 Å would be difficult to obtain. However, with FIB, the biggest advantages are: no need for mask generation or alignment, no lithography required, *in-situ* monitoring, *in-situ* deposition of electric contacts, small minimum feature size (from a couple of micrometer down to hundreds of nanometers), and short lead time when fabricating few MTJs.

In the ESCA process, the MTJ patterns had to be transferred to the sample using UV lithography before the ion milling could be performed. Also, all other process steps had to be performed in different systems accumulating to a lead time significantly longer than with the FIB scheme. Because of the need for lithography comprising for instance mask alignment with micrometer precision, the ESCA scheme would not work well on MTJs smaller than some tens of micrometres as long as UV lithography is used.

A major advantage with the ESCA process is that the argon milling does not affect the MTJ performance. In addition, the broader ion beam in the ESCA equipment was able to scan over an area of 4x4 mm, enabling the simultaneous fabrication of an array of MTJs. These two advantages, together with the possibility of stopping the etch process precisely at the desired layer of the TMR stack, made the ESCA process very competitive to the FIB above.

To conclude, some general remarks can be made: The FIB process provides the possibility of very quick fabrication of a few MTJs, but brings with it the Ga implantation problem. Perhaps this process is most suitable for a quick, first-time check on a TMR stack. For maximal performance of the TMR stack in MTJs, the ESCA process, albeit the longer lead time, is strongly recommended. Thus, depending on the stage of the investigation, therewith requirements of the experiments, both two processes for rapid prototyping are useful.

Future work. The material issue stressed on here, was the Ga implantation resulting from the FIB milling process, and the absence of deteriorating implantation effects with the ESCA. Material re-deposition on the vertical walls of MTJs when physical etching processes are employed, have been reported to have a deteriorating effect on the MTJ performance [2]. In the near future, this effect will be examined for the two rapid prototyping methods studied here.

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