

Ion Beam Milling for Structuring of Tunnel-Magneto-Resistance Sensors

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Abstract

We demonstrate that high quality tunnel-magneto-resistance (TMR) sensors composed of CoFeB/MgO/CoFeB magnetic tunnel junctions (MTJs) can be produced by using ion beam etching to structure the layer stack with a scia Mill 200. Background information about the MTJs functionality as well as sample preparation and the ion beam milling process are given. Required tool capability, such as helium backside cooling and etching uniformity, are analyzed. Finally, the MTJs were characterized by measuring the electrical resistance in a magnetic field.

Introduction

The tunnel-magneto-resistance effect (TMR) is used in modern high-precision sensors ranging from angular position sensors in automotive industry to read-out sensors in hard-disk-drive industry. Comparing to standard giant-magneto-resistance (GMR) sensors, the TMR has a higher thermal stability and increased signal output while decreasing the sensor's power consumption.

These advantages lead to a rapidly growing market for TMR sensors. However, the multilayer composition of the TMR sensor (Figure 1) causes issues regarding the necessary etching, which is essential for electrical contacting of the sensor. Classical dry-etching methods are limited due to the generally poor reactivity of magnetic materials, like CoFe, CoPt or NiFe. Additionally required reactive gases, like chlorine, can lead to after-corrosion of the sensor electrodes.

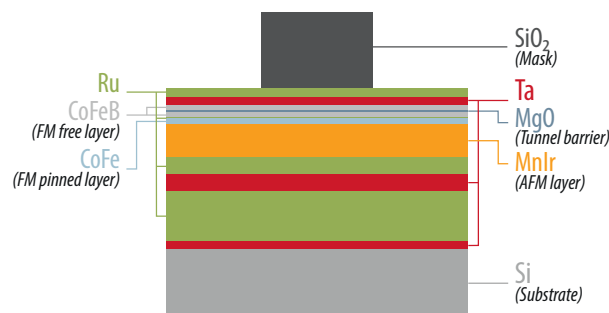


Figure 1: Typical TMR layer stack with hard mask on top

Ion beam milling with argon ions physically remove the magnetic layers. The ion beam source manufactured by scia Systems enables a precise tuning of the ion density and ion energy. Due to the ion bombardment, the argon ion beam milling allows to remove all materials used in the TMR stack in contrast to chemical etching. Furthermore the ion beam milling with inert gases, like Argon, suppresses any after-corrosion effects. In contrast, these corrosion effects lead to an increase in the specific metal resistance during dry etching. Operating with helium-backside wafer cooling, keeps the wafer temperature low and enables the processing of photoresist.

The paper provides background about the TMR function and layers as well as the ion beam milling technology performed by a scia Mill 200 from scia Systems. An analysis of the required tool capabilities for TMR etching is presented. Finally, details about the TMR etching and performance are shown.

Background TMR

A magnetic tunnel-junction (MTJ) is composed of two ferromagnetic (FM) layers with a thin non-magnetic, electrically insulating layer sandwiched between them as shown in figure 2. Electrons can tunnel through this barrier from one FM layer to the other, with their spin conserved. The upper FM layer is soft magnetic, i.e., its magnetization can easily be changed by applying an external magnetic field. It is thus called the free layer. The lower FM layer is, in contrast, hard magnetic and called the pinned layer, i.e., a stronger magnetic field is required to change its magnetization than in the case of the free layer. A reversal of the relative magnetic orientation of these two layers can thus be accomplished by applying an external field that is strong enough to change the magnetization of the free layer, but too weak to affect the pinned layer (Figure 2). This induces a change in electric resistivity, caused by a different probability of the electrons to tunnel through the barrier. The tunneling probability is higher for a parallel (P) magnetization of the FM layers and lower for an antiparallel (AP) magnetization. Accordingly, the TMR is higher for the AP than for the P magnetic orientation, an effect first observed in 1975 [1]. The magnitude of the TMR is expressed by the magnetoresistance ratio

$$\frac{\Delta R}{R} = \frac{R_{AP} - R_P}{R_P} \quad (1),$$

where R_{AP} and R_P are the respective resistances for the AP and P magnetic states [2, 3]. Today, MTJs based on CoFeB/MgO/CoFeB form the backbone of high quality spintronic devices. Records for the TMR lie at 604% at room temperature and 1144% at 5 K for these materials [4].

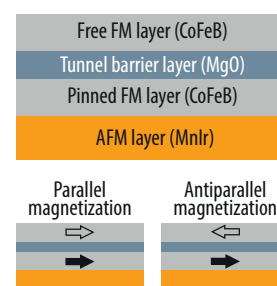


Figure 2: Magnetic tunnel junction based on CoFeB/MgO/CoFeB

Background TMR Sample Preparation

The magnetic stacks used in this study are composed of various layers deposited by magnetron sputtering on a Si substrate with a SiO₂ layer formed on top (see Figure 1). An underlayer consisting of 5 nm Ta, 30 nm Ru and again 10 nm Ta and 10 nm Ru is deposited first, followed by an

antiferromagnetic layer of 20 nm MnIr. This layer is used to exchange-bias the pinned layer, consisting of 3 nm CoFe. This, combined with 0.8 nm Ru and 3 nm CoFeB, forms an artificial antiferromagnet, followed by the tunneling barrier, composed of 1.7 nm MgO, and the free layer, composed of 3 nm CoFeB. Finally, a cap layer of 5 nm Ta and 5 nm Ru is deposited on the stack. The samples are annealed at 360 °C for 60 min in an external field of about 5500 Oe. By this process step, pinning is induced and the MgO layer is crystallized. The completed stack is then patterned by masks made of positive photoresist for the formation of the upper contacts.

Background Ion Beam Milling

The TMR stack was etched in a scia Mill 200 equipped with a RF350-e ion beam source as shown in Figure 3. The source is built in a three-grid configuration, where the plasma grid is applied to a positive potential, that directly adjusts the energy of the extracted ions and thus influences the etching rate. Plasma excitation is performed with an inductively-coupled plasma design, where the RF power is the degree of freedom for plasma density adjustment. Argon is used as process gas.

The system works in a face-down configuration to minimize particle contamination. The wafer is moved face-up into the chamber by an industry handling robot and is clamped automatically. A design with carrier handling is possible as well.



Figure 3: Left: Cluster configuration of scia Mill 200. Right: Ion beam source RF350-e.

By tilting the substrate holder, the angle of incidence can be adjusted between 90° and 150° (face-down). This allows a wide range of variation for process integration. By rotating the wafer a homogeneity < 1 % can be reached which is shown in detail later. The substrate temperature is kept low, due to a helium backside cooling that allows a sufficient thermal contact between the substrate and the water-cooled substrate holder.

Results: Process Performance of the scia Mill 200

For processing of wafers covered with a photoresist mask, the wafer temperature should not exceed a certain level, depending on the used photoresist. In Figure 4, an example of the wafer temperature with and without helium backside cooling is shown. Without helium backside cooling the wafer temperature goes up to 160°C and causes damages of the resist. With helium backside-cooling the wafer temperature remains at 60°C under the same process conditions. This keeps the photoresist intact and thus allows the process integration. The detected helium leak rate is < 0.5 sccm. The reason for the high wafer temperature without the helium backside-cooling is the limited thermal transport in vacuum. The mechanical contact between the wafer and the water-cooled surface is very small, wherefore temperature transport is dominated by the small

amount of radiation as convection is not present in vacuum. Therefore the resulting thermal contact is much smaller than the energy transferred into the wafer by the ion beam, what finally leads to a high wafer temperature.

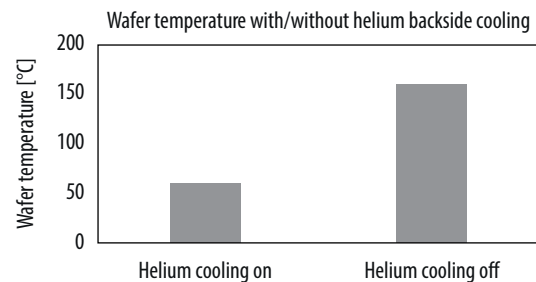


Figure 4: Wafer temperature with and without the use of helium backside-cooling.

The etching process is directly controlled by secondary ion mass spectrometer (SIMS), which detects in-situ the removed material on-the-fly, by measuring the secondary ions. With this technique, the etching can be stopped at a certain layer e.g. at the 1.7 nm thick MgO or the 5 nm thick Ta bottom-layer, both chosen in this study. The small layer thicknesses require a certain etch uniformity depending on the overall layer thickness above the etch-stop (see Figure 5). As example, a top-layer thickness of 13 nm had to be removed before entering the MgO layer. This requires a minimum etch-uniformity of < +/- 6.5 % at the MgO layer (gray points in Figure 5). More critical is the etch-stop at the 5 nm thick Ta bottom-layer, where about 95 nm material had to be removed. This leads to a uniformity requirement below +/- 2.6 % for the studied layer stack, in order to get a high yield for all devices e.g. on a 200 mm wafer. In industry practice the allowed range is smaller compared to the values given in Figure 5. The reason is, that only the etch-stop material has to be exposed at the etch-stop while taking any manufacturing tolerances into account.

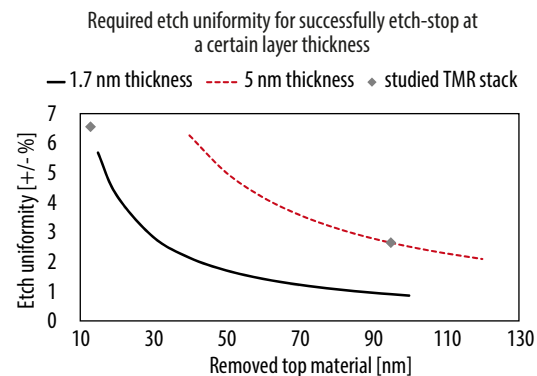


Figure 5: Calculated uniformity to successfully etch-stop at a 1.7 nm or 5 nm thick layer as a function of the removed top thickness which depends on the device layout. The grey points indicate the top thickness of the TMR stack in this study.

The etch uniformity of a scia Mill 200 was studied as a function of the angle of incidence. Starting at 0°, the achieved uniformity on 150 mm is +/- 1.5°. It decreases down to +/- 0.7 % when moving to an angle of 60°. On 200 mm wafer, the etch uniformity at 0° is +/- 4.0 % and decreases down to +/- 1.8 % at 60°. For the applied angles of 20°, 30° and 65°, the required uniformity of < 2.6 % for an etch-stop at 5 nm Ta was achieved. Hence, the process is suitable for mass production of TMR devices.

Results: TMR Stack Etching

The patterned TMR was processed in a scia Mill 200 with optional dual ion beam deposition (DIBD) for in-situ encapsulation after etching. To investigate the influence of different milling angles, some stacks are milled at an angle of incidence of 30° perpendicular to the sample surface (see Figure 6 (a)) and others at two different angles (see Figure 6 (b)). The first layers are milled at a steeper angle of 20° around the mask, until the MgO tunnel barrier is reached. All following layers are removed under a shallower angle of 65° in order to avoid redeposition of conductive material at the insulating barrier. At the same time, the ion beam cleans the lateral faces of the layers.

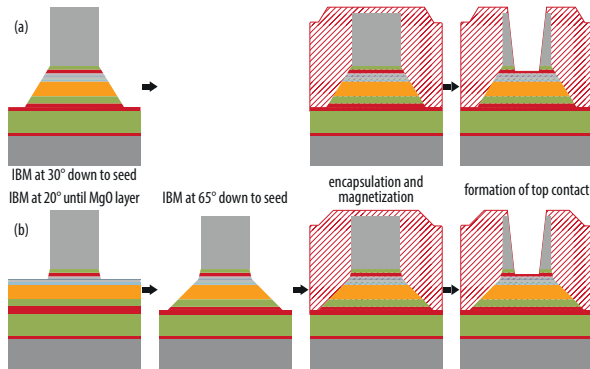


Figure 6: Cross-section of the CoFeB/MgO/CoFeB MTJ showing the manufacturing process. After depositing all layers and the masks, the stack is milled down to the seed, encapsulated with Ta₂O₅ and magnetized. In a final step, the top contact is formed. Milling is either performed at an angle of 30° (a) or at 20° to the MgO tunneling barrier and then at 65° down to the seed (b).

The milling process is controlled by SIMS to detect the layer boundaries and determine the mill stop for the lower contact as well as the changing point for the angle (see Figure 7). The spectrometer is sensitive to layer thicknesses in the sub nm range, making it possible to detect all layers in the stack and thus precisely define the end points. Prior to contacting the layers, they need to be encapsulated by an insulator. For this purpose, 120 nm Ta₂O₅ are deposited in situ by DIBD, using a metallic Ta target and additional added oxygen as a reactive background gas. The ion beam from the sputter source is focused on the target, sputtering the material that should be deposited on the substrate. The assist source (the ion source formerly used to remove the unmasked layer stack) is applied to improve the properties of the deposited layer.

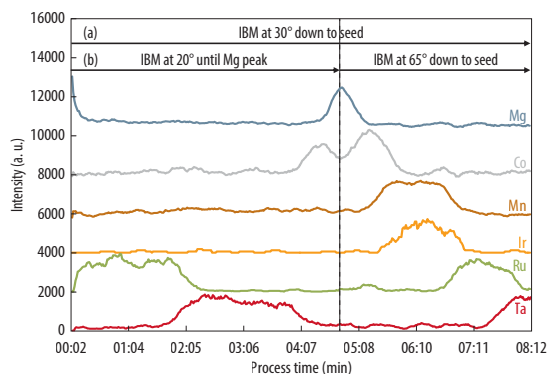


Figure 7: Signals for different materials present in the layer stack detected by the SIMS. The layer boundaries and thus the mill stops can be determined. (a) Stack is milled down to the 10 nm Ta layer. (b) Stack milled down to the 1.7 nm MgO tunneling barrier, then the angle is adjusted and the milling is continued until the 10 nm Ta layer is reached.

The TMR stack was analyzed regarding its TMR in an applied magnetic field. A major (left) and a minor (right) hysteresis loop are shown in Figure 8 for MTJs milled at 30° (Fig. 8 (a)) and $20^\circ/65^\circ$ (Fig. 8 (b)). The graphs show a TMR value of 140% for 30° and 90% for $20^\circ/65^\circ$. If the range of the applied magnetic field is high enough, both the exchange biased pinned layer and the free layer can be switched (major loop). The TMR values decrease with the applied field in both directions, with a sharp drop for the switching of the free layer and a smoother decrease for the pinned layer. By choosing a more limited field range, only the magnetization of the free layer can be changed whereas that of the pinned layer cannot (minor loop). A steep fall of the TMR value can be observed for 30° while it drops at a shallower angle for $20^\circ/65^\circ$.

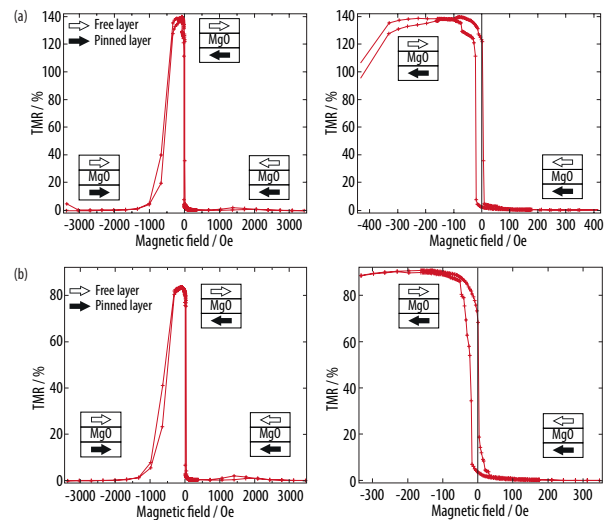


Figure 8: TMR plotted versus the applied magnetic field. By selecting a high enough field range, both the exchange biased pinned layer and the free layer can be switched (left). In a reduced field range, only the pinned layer.

The shallow angle of 65° in (b) was chosen deliberately in order to avoid bypasses by redeposition of metal at the MgO barrier. The TMR measurements show, high values for the 30° sample as well, indicating a lack of critical sidewall deposition also for this angle. The shallower drop of the TMR value compared to the 30° device may indicate a rougher free layer supporting the lower TMR value for this sample. It makes a statement about the angle dependency of the TMR difficult. This needs to be clarified in a following experiment, in which also the geometry of the device edges could be examined by e.g. SEM.

Summary

In this study, different aspects important for the TMR etching were considered. The paper is divided into two different aspects: studying a part of the TMR manufacturing process and analyzing hardware requirements for an ion beam milling tool.

In the first part, the deposition, etching and finally analyzing was performed. We demonstrated that high TMR values can be obtained for Co-Fe-B/MgO/Co-Fe-B MTJs by depositing the insulator in situ subsequent to milling. Using a SIMS enables to detect all layers while milling, thus all mill stops can precisely be defined. A TMR value of 140% could be measured for a milling angle of 30° and 90% for the two step milling process with $20^\circ/65^\circ$.

In the second part, tool hardware requirements for TMR stack etching were considered. One main aspect is the processing of the photoresist

which has to be kept intact for reasons of process integration. By using a helium backside cooling, an efficient thermal contact between the wafer and the water-cooled substrate holder was achieved. With this technique, a wafer temperature of 60°C was reached. The etch-stop specification was analyzed by calculating the required etching uniformity. Etching process optimization with a scia Mill 200 yield the necessary uniformity. Additionally, a SIMS was installed at the systems which allows the direct process control and precise etch-stop.

Literature

- [1] M. Julliere, Tunneling Between Ferromagnetic Films, Physics Letters A 54, 225-226 (1975); DOI: 10.1016/0375-9601(75)90174-7
- [2] J. S. Moodera, L. R. Kinder, T. M. Wong, R. Meservey, Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions, Physical Review Letters 74, 3273-3276 (1995), DOI: 10.1103/PhysRevLett.74.3273
- [3] T. Miyazaki, N. Tezuka, Spin polarized tunneling in ferromagnet/insulator/ferromagnet junctions, Journal of Magnetism and Magnetic Materials 151, 403-410 (1995), DOI: 10.1016/0304-8853(95)00563-3
- [4] S. Ikeda, J. Hayakawa, Y. Ashizawa, Y. M. Lee, K. Miura, H. Hasegawa, M. Tsunoda, F. Matsukura, H. Ohno, Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature, Applied Physics Letters 93, 082508 (2008); doi: 10.1063/1.2976435