A TEM structural study of thermal stability of magnetic tunnel junctions integrated with CMOS devices

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Abstract. We present a TEM/STEM study of the structure and thermal stability of Co/AlOx/Si, CoFe(B)/MgO/Si and FeNi/SiOx/Si magnetic junctions deposited directly on patterned Si. In all three types of junctions the films are uniform and continuous. Annealing at 300 at 550 °C does not change their structure. CoFe and CoFeB layers remained amorphous after the annealing process.

1. Introduction

Magnetic Random Access Memory (MRAM) is emerging as a strong candidate for non-volatile memory offering permanent storage, high speed, high density and low power consumption. Current technologies employ back end implementation of MRAM with standard CMOS circuitry. Many of the problems associated with the production of MRAM including scalability and reliability of back end processes can be overcome by introducing a front end magnetic module (FEM). FEM is a process in which deposition of the spin polarized injector and collector is done directly on the Si substrate [1]. Each magnetic module consists of a tunnel barrier, a thin ferromagnet (FM) and a capping layer, deposited directly onto Si. Spin polarized current is injected from one magnetic electrode to a second FM collector through a suitably doped Si substrate. The magnetisation of the injector electrode is fixed, thus serving as the reference memory state while the magnetisation of the collector electrode can be switched to form the memory input.

A major challenge for achieving such MRAM is the ability to deposit in a controlled way an oxide barrier and FM layers into patterned trenches directly on Si, as well as the thermal stability of these new devices during the processing of the CMOS components (450 °C for 1 hour). Therefore, the first objective is to determine which materials satisfy these requirements. In this paper we present a TEM/STEM study comparing the structures of as-deposited Co/AlOx/Si, TaN/CoFe(B)/MgO/Si, Ta/FeNi/SiOx/Si and annealed TaN/CoFe(B)/MgO/Si films deposited directly on Si.

2. Experiment

We have grown magnetic tunnelling junctions on Si with three different oxide barriers, which are AlOx, MgO and SiO2. AlOx films were grown by atomic layer deposition, consisting of growth of Al
monolayers followed by subsequent oxidation of each monolayer. MgO films were deposited by RF sputtering using an MgO target, while SiO$_2$ films were grown by thermal oxidation of Si substrates. The ferromagnetic electrodes consist of Co, CoFe, CoFeB and NiFe. All films were deposited at room temperature. The CoFeB/MgO/Si magnetic junctions were annealed at 300 and 550 °C for 1 hour.

The structural characterization of the magnetic junctions was performed by Bright Field TEM (BF), High Resolution TEM (HRTEM), and High Angle Annular Dark Field imaging (HAADF), as well as Energy Filtered TEM (EFTEM) mapping, Electron Energy Loss Spectroscopy (EELS) and quantitative Energy Dispersive X-ray spectroscopy (EDX) using a JEOL 3000F microscope. The TEM specimens were prepared by mechanical thinning, dimpling, polishing and low energy ion milling.

3. Results and Discussion

3.1 Co/AlO$_x$/Si magnetic junctions

Figure 1a is a cross-sectional BF-TEM image that shows a trench in a patterned Si wafer into which an AlO$_x$ barrier and a Co FM layer are deposited. Both the barrier and the FM layer are uniformly deposited within the trench. HRTEM was used to measure the thickness of the barrier and the roughness of the Si/AlO$_x$ and AlO$_x$/Co interface. Two sets of samples with nominal thicknesses of 2.5 and 4.0 nm of AlO$_x$ barrier were analyzed. For the first set, the measured thickness of the barrier is 2.4 nm and the roughness is 0.5 nm, while for second set the barrier thickness is 3.9 nm and the roughness is 0.5 nm (Fig. 1b).

The roughness at the Co/AlO$_x$ interface is similar to that at the Si/AlO$_x$ interface, which implies that that roughness of the interface between the electrode and barrier is determined by the quality of the Si surface. The effect of thermal annealing on the AlO$_x$ films was studied by Auger electron spectroscopy. Auger spectra have shown that the chemical structure of the barrier is not changed even at annealing temperatures of 700 °C for 1 hour [2].

3.2 TaN/CoFe(B)/MgO/Si junctions

The MgO barrier and CoFeB films were deposited in Si patterned trenches by sputtering. Cross-sectional BF and HRTEM images (Figs. 2 and 3a, respectively) from the deposited layers show that the layers are continuous and with a constant thickness (the TaN top-layer is used as a capping layer). The HRTEM image (Fig. 3a) shows distinctly the amorphous MgO tunnel barrier with a thickness of 3.0 nm, and amorphous CoFeB film with a thickness of 2 nm, followed by 10 nm of the TaN capping layer. Significant deposition of all the layers is present on the walls of the trenches in comparison with the atomic layer deposition growth. When this structure is annealed at 300 and 550 °C, both the MgO
barrier and CoFeB layer remained amorphous (Fig. 3a). Annealing promoted crystallization is observed only in the TaN capping layer. This thickness of the FM layer is the most likely factor, which prevents the crystallization of the FM layer even at annealing temperatures of 550 °C. The control experiments of the same structure that use CoFe instead of CoFeB electrode show that the FM layer (CoFe) is still amorphous even after annealing at 550 °C (Fig. 3b). These results are in agreement with recently reported data that CoFe crystallization is a thickness dependant phenomenon [3], namely when the FM films (CoFe or CoFeB) are thinner than 2 nm, they remain amorphous even after annealing at high temperatures. The HRTEM images also show contrast variations in the capping layer. An O elemental EFTEM map (Fig. 4a) from the junction layers shows two spatial bands. The first band corresponds to apparent oxidation of the capping layer while the second is attributed to the MgO barrier. Intensity profiles indicates that 2.5 nm of the capping layer is oxidized (Fig. 4b), while the thickness of the barrier is 3.2 nm, which is in agreement with HRTEM data.

Fig. 2. BF-TEM image from a patterned trench in Si, into which a CoFeB/MgO structure was deposited

Fig. 3. HRTEM image from a CoFeB/MgO/Si (a), and CoFe/MgO/Si (b) contacts at the bottom of the trench

Fig. 4. a) EFTEM O map from a CoFeB/MgO/Si junction, b) integrated intensity of the O signal perpendicular to the junction shown in a)

Fig. 5. STEM HAADF image from CoFeB/MgO/Si contact and line scan EELS profile. O (1), N(2) and Fe (3) line profiles across the junction are presented. Vertical lines show nominal layer boundaries.
EELS line scan spectra across the layers confirm the results of the EFTEM mapping. Fig. 5 also shows the presence of two O bands. The FM elements Fe and Co diffuse toward the barrier and capping layers while N diffuse mainly toward the barrier. It is interesting to note that the MgO barrier act almost as a diffusion barrier of N into Si.

3.3 Ta/FeNi/SiO2/Si junctions
Bright Field (BF) and HRTEM imaging of these specimens patterned by optical lithography show that the SiO2 barrier is mostly uniform in thickness (2 nm) while the interface between the oxide and Si substrate is rough (Fig.6 and Fig.7). The roughness of this interface is mainly due to the Si substrate, which is attributed to over-etching. This roughness of the interface results in non-flat FM layers. The FM layer is homogeneous and also present at the side walls of the holes (Fig.6) with slight compositional variations (Fig.8). The thickness of the FM layer on the sidewall is approximately 50-80% of the contact thickness.

4. Conclusion
In the three studied magnetic junctions embedded in Si, the oxide barrier is continuous. For the SiO2 barriers, a small concentration of pinholes is present. The FM layers are also continuous and homogeneous in composition. The structure of these junctions remains mostly unchanged during the annealing process, which indicates that this type of structures can be successfully employed in fabrication of the Si embedded MRAM.

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