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TEM and PEELS Study of Mn Diffusion in an MRAM Structure

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The Mn diffusion phenomenon in a megnetoresistive random access memory (MRAM) multilayer stack is studied using a transmission electron microscope (TEM) and a parallel electron energy-loss spectrometer (PEELS). Thermally activated Mn diffusion to the interface of the Al_2O_3 tunneling barrier and ferromagnetic NiFe might be responsible for the drop of tunneling magnetoresistance (TMR) in MRAM bits.

The TEM sample was prepared by using a focused ion beam (FIB) technique. TEM and PEELS analyses were performed on JEOL2010F with a Gatan GIF-PEELS system. FIG. 1A shows a Z-contrast, high-angle, annular dark-field STEM image of the multilayer (Ta/MnIr/NiFe/Al_2O_3/NiFe/Ta). PEELS (FIG. 1B) data was collected with the electron beam scanning across the structure, along the line indicated in FIG. 1A. From the Mn profile (FIG. 1B), we observed the diffusion of Mn through the NiFe layer into the Al_2O_3 layer. In transition metals, L_3 and L_2 white lines ($2p^{3/2} \rightarrow 3d^{3/2}3d^{5/2}$, $2p^{1/2} \rightarrow 3d^{3/2}$) are observed in the energy-loss spectra [1]. The comparison of the Mn $L_{2,3}$ edges from the MnIr layer and NiFe/Al_2O_3 interface (FIG. 2A) shows a significant difference in the fine structures. The intensity ratio of L_3:L_2 is much larger for diffused Mn in Al_2O_3. It has been shown that the relative intensities of L_3 and L_2 of Mn are highly sensitive to the 3d occupancy and thus the valence state [1–3]. The spectra, as shown in FIG. 2A, were processed using the Fourier ratio method for removing the plural scattering effect [4]. The intensity ratio of white lines $I(L_3)/I(L_2)$ is calculated from the spectra using the double-step background fitting procedure with the step at the peak [1, 2]. FIG. 2B plots $I(L_3)/I(L_2)$ vs. the Mn valence state for the reference data (ref. [2]) and for the data from the current study. From the correlation of our current data ($I(L_3)/I(L_2) \cong 3.3$ for Mn in Al_2O_3) to the reference data, we conclude that the mean valence state of Mn in Al_2O_3 is ~ +2.2. Thus, Mn diffused into the Al_2O_3 layer and accumulated there in an oxidized state.

The temperature effect on the Mn diffusion was studied. The PEELS analysis was repeated on samples with different thermal treatments (no annealing, annealed at 220°C, annealed at 250°C). It was observed that the Mn amount in the Al_2O_3 increases with annealing temperatures. The relative Mn:O ratio at the NiFe/Al_2O_3 interface was calculated from the elemental profiles. The Mn:O ratio is qualitative at this stage, mainly because the NiFe/Al_2O_3 interface roughness and sample tilt affect the measured Mn:O ratio. To minimize this variation, the Mn:O ratio was calculated by integrating the elemental profile over a 3nm range around the Mn peak location at the NiFe/Al_2O_3 interface. The measured Mn:O ratio at the interface, as a function of annealing temperatures, is shown in FIG. 3, where there is a significant increase of Mn diffusion with a higher annealing temperature. The existence of diffused Mn in the nonannealed sample indicates that the Mn diffusion occurred during the MRAM production process.

References

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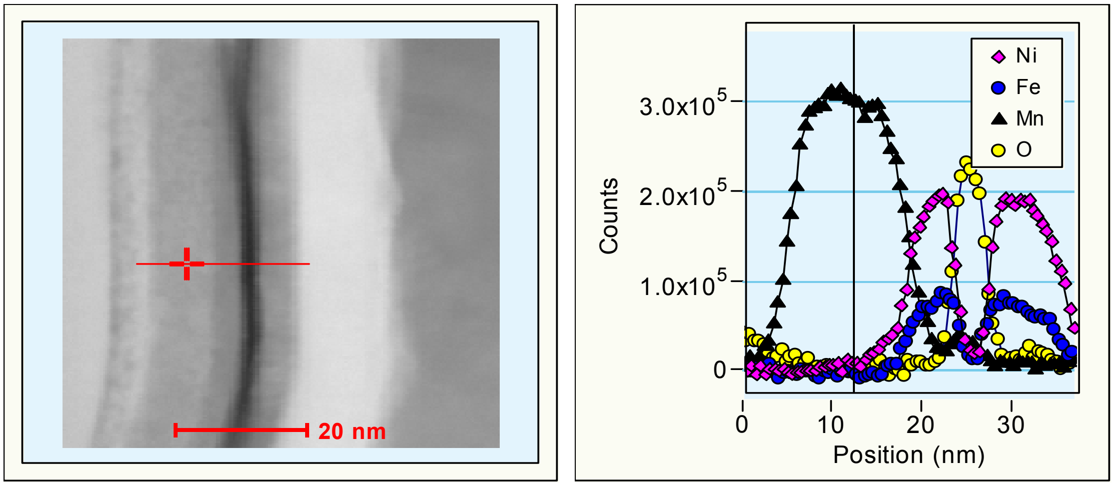
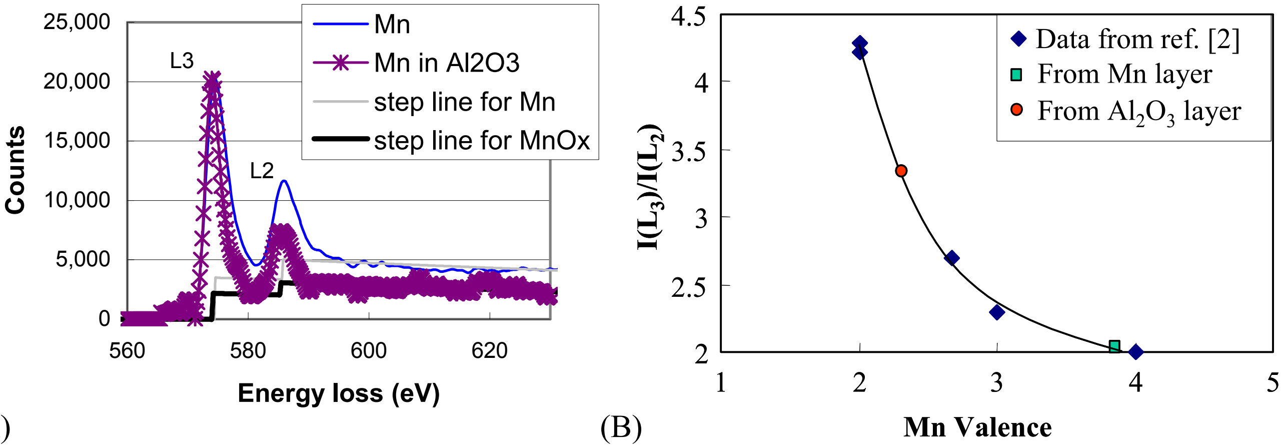


(A) (B)

FIG. 1. (A) STEM image of the magnetic stack. (B) Elemental profiles obtained using PEELS signal as the electron beam scanned along the line in (A) from left to right.



(A) (B)

FIG. 2. (A) Comparison of Manganese $L_{2,3}$ edge spectra from Mn layer and from Al_2O_3 layer. (B) A plot of white line intensity ratio $I(L_3)/I(L_3)$ versus the valence state of Mn.

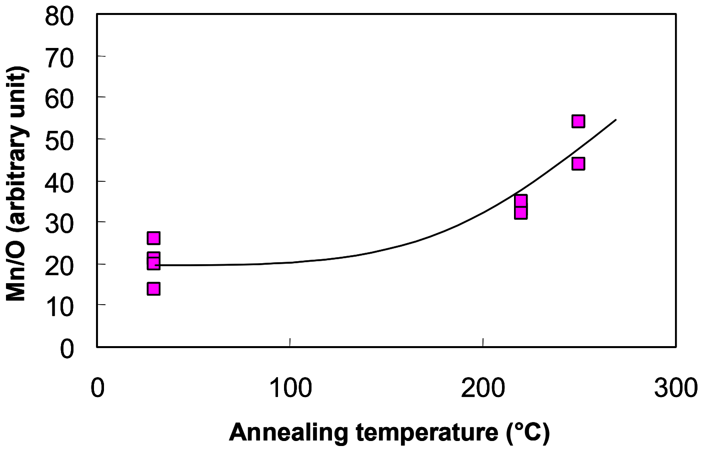


FIG. 3. Mn:O ratio at the NiFe/Al_2O_3 interface as a function of annealing temperature.