Preoxidation as a General Approach to Suppressing Orange-Peel Coupling in Magnetic Tunnel Junctions

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We have found that preoxidation of the bottom electrode prior to deposition of Al_2O_3 or MgO is very effective as a general approach to suppressing orange-peel coupling in magnetic tunnel junctions. When orange-peel coupling is suppressed, the hard-axis saturation field of the free layer is greatly reduced.

***Index Terms*—Magnetic tunnel junctions, orange-peel coupling, preoxidation.**

I. INTRODUCTION

RECENTLY we reported that preoxidation of the bottom Co electrode in Co/Al_2O_3/Co magnetic tunnel junctions (MTJs) is an effective way of suppressing orange-peel coupling and that the approach is consistent with high-quality MTJs [1]. Orange-peel coupling is a common problem when MTJs are used to detect low magnetic fields [2]. As illustrated in Fig. 1, this form of coupling is associated with conformal roughness, which produces magnetic poles that favor parallel alignment and act as a coupling field. This coupling field reduces the sensitivity of the free layer to small magnetic fields.

Fig. 2 presents data on the coupling field for three different nonmagnetic spacer layers (SL) in structures of the general type Co/SL/Co. The coupling field is measured as the shift from zero field of the center of the easy-axis hysteresis loop. The estimated accuracy of the measurement is ±2 Oe. The three SLs exhibit very different coupling fields. When Cu is used the structure is a spin valve, and the coupling field rises sharply for spacings below 2 nm, as is typical for spin valves. When a MTJ structure is made in the conventional manner of depositing metallic Al and subsequently oxidizing it, the coupling is somewhat smaller than in a typical spin valve, but still large enough to be problematic for thicknesses of $\approx$1 nm that are desirable for MTJs. A dramatic drop in the coupling field is observed when the Co surface is lightly oxidized before Al_2O_3 deposition. The exposure used for Fig. 1 was 10^{-3} Pa ($\approx 10^{-5}$ Torr) O_2 for 10 s. However, the exact time of O_2 exposure is not particularly critical since after a few seconds the rate of surface oxidation decreases sharply.

The remarkable feature of this preoxidation is that the coupling field scarcely rises as the Al_2O_3 thickness decreases from 5 to 0.5 nm. Clearly, the orange-peel coupling has been suppressed to a remarkable extent.

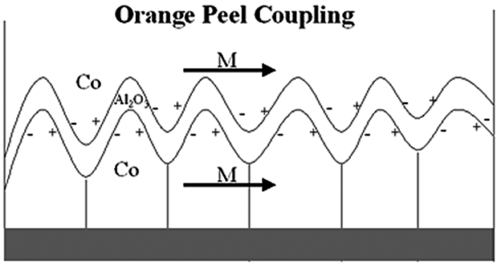

Fig. 1. A schematic illustration of orange-peel coupling, based on conformal roughness. The vertical lines represent grain boundaries. The growth is columnar. The plus and minus signs represent the magnetic poles at the bumps on Co. The poles act as a coupling field favoring parallel alignment of the magnetization. The height of the bumps is greatly exaggerated, for clarity, relative to the grain diameters. Note also that grain diameters in MTJs are typically 10 times larger than the Al_2O_3 thickness.

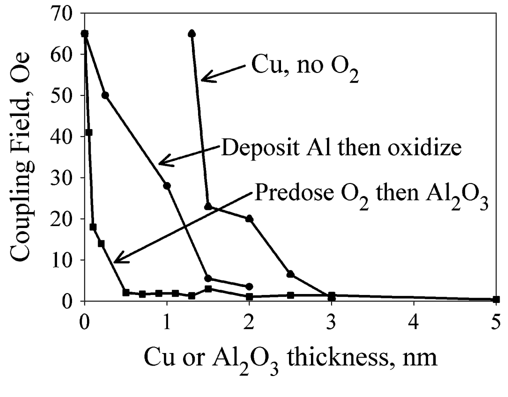

Fig. 2. Plots of the coupling field versus thickness for nonmagnetic (NM) spacer layers in Co\NM\Co structures. The NM spacer layers are Cu with no oxygen used in any way, Al deposited as metal and oxidized subsequently, and preoxidation of the Co before Al_2O_3 deposition.

II. EXPERIMENTAL

All films were deposited on Si(100) wafers with 250 nm of thermal oxide. Wafers were cleaved into ~1 cm^2 pieces, cleaned

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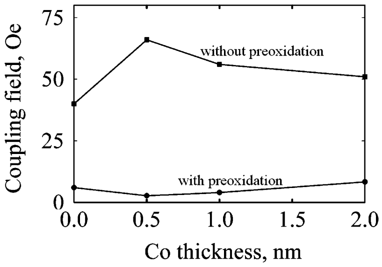

Fig. 3. Plots of the coupling field versus bottom Co thickness for a $Co\backslash Al_2O_3\backslash Co$ structure with and without preoxidation of the Co surface prior to the Al_2O_3 deposition.

ultrasonically in a glassware cleaning solution, rinsed in distilled water, blown dry with inert gas, and installed in the deposition chamber. After bakeout, the deposition chamber has a base pressure of 7×10^{-8} Pa (5×10^{-10} Torr), of which 90% is H_2. The films were deposited at room temperature by dc-magnetron sputtering in 0.3 Pa (2 mTorr) Ar at a typical rate of $\sim$1 nm/min. To preoxidized samples, 10^{-3} Pa ($\approx 10^{-5}$ Torr) O_2 was admitted to the chamber and there was a 10 s delay prior to turning on the magnetron gun and depositing the oxide layer by reactive sputtering. For samples not preoxidized, Al or Mg metal was deposited and subsequently oxidized by an oxygen plasma. The magnetic hysteresis loops shown here were recorded in air using a BH looper.

III. RESULTS AND DISCUSSION

To test the generality of these results we have expanded our investigations into other MTJ configurations with different layer materials and thicknesses. Fig. 3 presents coupling-field data for varying the bottom Co layer thickness with and without preoxidation of this layer prior to the Al_2O_3 deposition. The full structure is Si(100)$\backslash SiO_2\backslash$20 nm $Ni_{77}Fe_{14}Cu_5Mo_4\backslash$X nm Co$\backslash$1 nm $Al_2O_3\backslash$2.5 nm Co$\backslash$10 nm $Ir_{20}Mn_{80}\backslash$5 nm Ta, and X is varied. The purpose of the $Ni_{77}Fe_{14}Cu_5Mo_4$ film is to make the free layer very soft. The results indicate that the coupling field is sharply reduced by preoxidation for all values of the bottom Co thickness.

In recent years, MTJs based on CoFeB alloys have been found to exhibit large TMR values [3]. We explore one such alloy in Fig. 4. The full structure is Si(100)$\backslash SiO_2\backslash$20 nm $Ni_{77}Fe_{14}Cu_5Mo_4\backslash$X nm $Co_{60}Fe_{60}B_{20}\backslash$ 1 nm $Al_2O_3\backslash$2.5 nm Co$\backslash$10 nm $Ir_{20}Mn_{80}\backslash$5 nm Ta, and X is varied. Again we find that the coupling field is sharply reduced by preoxidation for all values of the $Co_{60}Fe_{60}B_{20}$ thickness.

Although Al_2O_3 based MTJs were important a few years ago, they have recently been eclipsed by MgO based MTJs which tend to have much larger tunneling magnetoresistance [4]–[9].

In Fig. 5 we have explored the generality of the preoxidation effect in MgO MTJ structures as a function of MgO thickness. The full structure is Si(100)$\backslash SiO_2\backslash$20 nm $Ni_{77}Fe_{14}Cu_5Mo_4\backslash$1 nm Co$\backslash$X nm MgO$\backslash$2.5 nm Co$\backslash$10 nm $Ir_{20}Mn_{80}\backslash$5 nm Ta, and X is varied. Again, we find that the coupling field is sharply reduced for all values of the MgO thickness.

In Fig. 6 we investigate the alloy $Co_{40}Fe_{40}B_{20}$.The full structure is Si(100)$\backslash SiO_2\backslash$20 nm $Ni_{77}Fe_{14}Cu_5Mo_4\backslash$1 nm $Co_{40}Fe_{40}B_{20}\backslash$X nm MgO$\backslash$2.5 nm Co$\backslash$10 nm $Ir_{20}Mn_{80}\backslash$5 nm Ta, and X is varied. Again, we find that the coupling field is sharply reduced for all values of the MgO thickness.

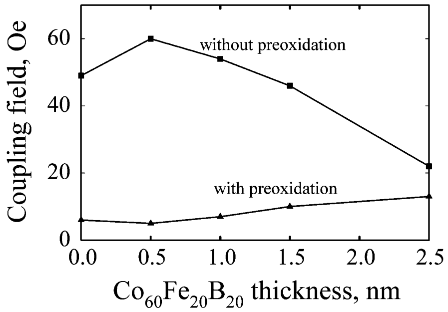

Fig. 4. Plots of the coupling field versus $Co_{60}Fe_{20}B_{20}$ thickness for a $Co_{60}Fe_{20}B_{20}\backslash Al_2O_3\backslash Co$ structure with and without preoxidation of the $Co_{60}Fe_{20}B_{20}$ surface prior to the Al_2O_3 deposition.

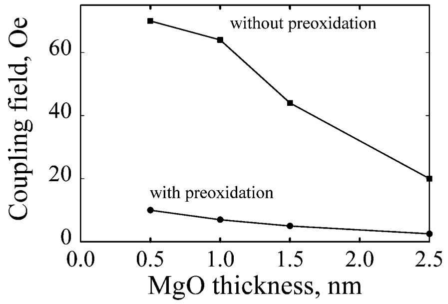

Fig. 5. Plots of the coupling field versus MgO thickness for a $Co\backslash MgO\backslash Co$ structure with and without preoxidation of the Co surface prior to the MgO deposition.

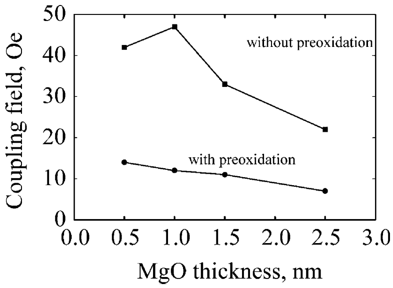

Fig. 6. Plots of the coupling field versus MgO thickness for a $Co_{40}Fe_{40}B_{20}\backslash MgO\backslash Co$ structure with and without preoxidation of the $Co_{40}Fe_{40}B_{20}$ surface prior to the MgO deposition.

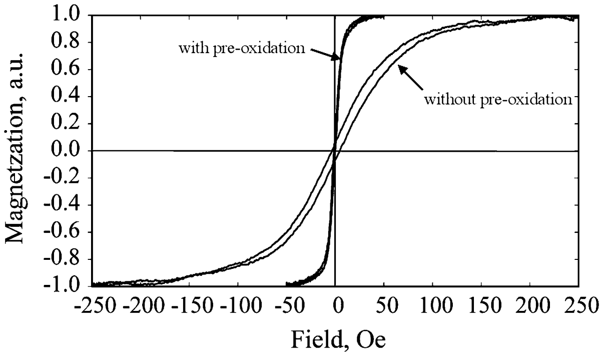

Fig. 7. An M-H plot in the hard axis for the samples in Fig. 3 with no Co, showing the dramatic softening of the free layer by preoxidation.

Fig. 7 illustrates the softening in the free layer produced by preoxidation. The data is for the two samples in Fig. 3 with no Co. The data is shown for the hard axis since it is more relevant for magnetic sensors.

Although more variations in samples could be imagined, these results presented here represent a reasonable attempt to establish the general validity of preoxidation as a beneficial effect in the fabrication of MTJs. As pointed out earlier, reasonably high values of the TMR can be achieved with preoxidation [1]. However, for the same amount of deposited Al the RA product is larger with preoxidation so thinner layers will be called for when small RA products are sought. It seems that preoxidation prevents the loss of Al into grain boundaries of Co, a process suppressed by preoxidation [10]–[13]. In any case, we know of no reason that preoxidation cannot be used a as standard practice for MTJ fabrication.

IV. CONCLUSION

1) Orange-peel coupling in MTJs may be very effectively suppressed by preoxidation of the surface prior to Al_2O_3or MgO deposition.
2) The suppression of orange-peel coupling allows the sense layer in the MTJ to be softer.
3) The effect is most pronounced for $Al_2O_3$and MgO thicknesses of 0.5 to 1.5 nm, which is the range of greatest importance for MTJs.
4) The effect is entirely consistent with large TMR values.

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