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Effect of field-annealing on magnetostriction and tunneling magnetoresistance of Co/AlO$_x$/Co/IrMn junctions

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ABSTRACT

The magnetostriction (λ_s) and tunneling magnetoresistance (TMR) of two Co/AlO$_x$/Co/IrMn MTJ systems that were deposited on Si(1 0 0) and glass substrate were examined at RT and field-annealing with various thicknesses of AlO$_x$. One structure was a Si(1 0 0)/Ta/Co/AlO$_x$/Co/IrMn/Ta system, and the other was a glass/Co/AlO$_x$/Co/IrMn system. The experimental results reveal that, in the Si(1 0 0)/Ta/Co/AlO$_x$/Co/IrMn/Ta system, the ratio of TMR is maximal under the field-annealing condition, and is optimal at an AlO$_x$ thickness of 26 Å as well as in the RT condition. EDS analysis demonstrates that, these results are related to the distribution of Co and O atoms, because the oxidation of AlO$_x$ is most extensive at a thickness of 26 Å. In the glass/Co/AlO$_x$/Co/IrMn system, λ_s does not significantly vary under the RT condition; however, λ_s is maximized (−20 ppm) by field-annealing at an AlO$_x$ thickness of 17 Å. The abundance of Co and O in the system dominates the behavior of λ_s, according to EDS analysis. Finally, the minimum value of λ_s and the maximum ratio of TMR are −8 ppm and 60%, respectively, at an AlO$_x$ thickness of 26 Å under the field-annealing condition.

1. Introduction

Favorable combinations of characteristics of magnetic tunneling junctions (MTJs), including low magnetostriction (λ_s) and high tunneling magnetoresistance (TMR), are crucial to optimizing the performance of an MTJ device in high-temperature environments. Tolerance to high temperatures is important in read head sensors and magnetoresistance random access memory (MRAM) [1–3].

Generally, the AlO$_x$ layer, after field-annealing treatment, of an MTJ, which serves as a barrier to tunneling, increases the TMR value [4,5]. The TMR ratio of AlO$_x$-based MTJ has been found to increase with annealing temperature (T_A) up to 265 °C [6]. However, Mn atoms diffuse toward the tunneling barrier ($T_A > 350\,^\circ$C), reducing the TMR value [7].

Another important parameter, λ_s, is also important to MRAM applications. The signal is disturbed according to large λ_s when the device is in the process of reading/writing. Recently, λ_s and TMR of the AlO$_x$-based MTJ have been studied [8–11], but much remains to be explored. Chen et al. found that the maximum TMR and minimum λ_s were 36% and −15 ppm, respectively, in a Co/AlO$_x$/Co/IrMn junction at RT [11]. Accordingly, this investigation focuses on the values of TMR and λ_s in the field-annealed Co/AlO$_x$/Co/IrMn junction. Recent results show that field-annealing treatment can improve the magnetic properties of Co/AlO$_x$/Co/IrMn junctions. Additionally, the TEM results indicate that the Co/AlO$_x$ and AlO$_x$/Co interfaces are smooth, increasing higher the TMR values [12,13]. To determine how varying AlO$_x$ thickness (δt_o) varies the chemical composition of the AlO$_x$ barrier, a cross-sectional high-resolution transmission electron microscope (HRTEM) with the ability to obtain a nanoprobe energy dispersive spectrum (EDS) was utilized to analyze the distributions of Co, Al, O, Ir and Mn concentrations on the cross-section across the AlO$_x$ layers.

2. Experimental details

A cross-strip MTJ with the structure Si(1 0 0)/Ta(30 Å)/Co(75 Å)/AlO$_x$(δt_o)/Co(75 Å)/IrMn(90 Å)/Ta(100 Å) was deposited onto a Si(1 0 0) substrate by magnetron sputtering, where δt_o = 12, 17, 22, 26, and 30 Å. The IrMn layer was deposited using an alloy target with a composition of 20 at.% Ir and 80 at.% Mn. The TMR and λ_s of two sets of MTJ specimens, prepared using different treatments during deposition, were studied. The treatments were as follows: (a) substrate temperature (T_s) maintained at RT an in-plane deposition field, h = 500 Oe, and (b) T_s = RT with an in-plane deposition field, h = 500 Oe during deposition, with post-deposition annealing in the field at T_A = 250 °C for 1 h, before the samples were field-cooled to RT. The typical pressure of the base chamber was less than 1×10^{-7} Torr, and the pressure of the Ar working chamber was maintained at 5×10^{-3} Torr. Furthermore, the λ_s of the glass/Co(75 Å)/AlO$_x$(δt_o)/Co(75 Å)/IrMn(90 Å) MTJ, where δt_o = 12, 17, 22, 26, and 30 Å, was also measured using the optical-cantilever method following two treatments [14,15]. To increase the sensitivity and reduce the substrate effect, a glass

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substrate was used in the measurement of λ_s. The TMR ratio of the MTJ device that was deposited on the Si substrate was found, and this device was determined to be compatible with the semiconductor process.

To prepare an AlO_x barrier, Al was initially deposited on the bottom FM electrode (Co layer), and the AlO_x barrier layer was then formed by plasma oxidation in an oxidizing atmosphere of a mixture of Ar/O_2 in the ratio 9:16. The plasma oxidation time was varied from 30 to 70 s and the initial thickness of the Al layer was thus increased from 12 to 30 Å. Each MTJ was fabricated by the cross-strip method with a cross-sectional junction area of 0.0225 mm^2. The conventional four-point technique is adopted in a typical measurement of TMR ratio. To understand how varying δt_o alters the chemical composition of the AlO_x barrier, a cross-sectional HRTEM with EDS capability was employed to analyze the Co, Al, O, Ir and Mn concentrations (x_{Co}, x_{Al}, x_O, x_{Ir}, and x_{Mn}) across each AlO_x layer.

3. Results and discussion

Fig. 1 presents a typical cross-sectional HRTEM image of a Co(75 Å)/AlO_x(26 Å)/Co(75 Å) field-annealed MTJ. After field-annealing at 250 °C, the laminated structure of Co(75 Å)/AlO_x (26 Å)/Co(75 Å) MTJ had the following features, which may explain the general increase in TMR (Fig. 2) and the decline in λ_s (Fig. 3). First, the crystallinity of the Co layers on both sides improved as the degree of texturing after field-annealing increased, potentially increasing the spin polarization P of each Co layer. Second, the Co/AlO_x and AlO_x/Co interfaces had been modified to make them smoother with low waviness, due to field-annealing. Third, the AlO_x tunneling remained amorphous following field-annealing.

Fig. 2 plots the TMR ratio versus δt_o at RT following field-annealing at 250 °C. Before annealing at RT, as in our earlier investigation [11], the TMR ratio was initially low, increased from 21% to 36%, and finally declined to 24%. After field-annealing at 250 °C, the TMR ratio increased from 27% to 60% and then eventually fell back to 52%. In the range of δt_o from 12 to 22 Å, the TMR values of RT and field-annealed at 250 °C were approximately equal. In both cases, the TMR ratio was small, but it exceeded 20% in this range of δt_o. This finding may be attributed to the presence of pin-holes, which cause the spin scanning effect [16]. In contrast, the MTJ after field-annealing at 250 °C exhibited a much larger TMR ratio than the RT MTJ, reaching a maximum TMR ratio of 60% at $\delta t_o = 26$ Å. This result may follow from the improvement in the interface roughness and the Co crystallinity due to field-annealing [17]. Another possible cause is the polarization and depolarization of spin tunneling in the oxidation plasma process [11]. Briefly, if δt_o is too small (such as $\delta t_o = 12$ Å), then the Co bottom electrode may be over oxidized, causing the free Co layer to be less polarized, resulting in a lower spin-tunneling current. If δt_o is too high (such as $\delta t_o = 30$ Å), then the spin-polarized current may be depolarized excessively in the spin-tunneling process. This depolarization effect would also reduce TMR value. Moreover, the phenomenon of increasing- and -decreasing TMR ratio upon the RT and field-annealing at 250 °C of MTJs, shown in Fig. 2, may reveal that the spin-tunneling effect is also sensitive to the physical and chemical conditions of the two interfaces of the MTJ junction [18]. The oscillatory profile of the TMR ratio results from the inter-layer coupling effect, implying that ferromagnetic electrode coupling obeys Bruno's reflection model [13].

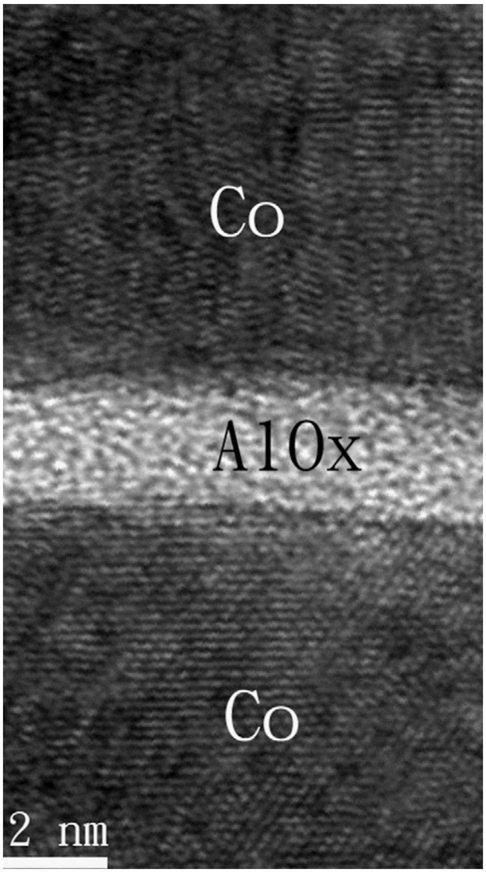

Fig. 1. Cross-sectional HR-XTEM image of Co(75 Å)/AlO_x(26 Å)/Co(75 Å) field-annealed MTJ.

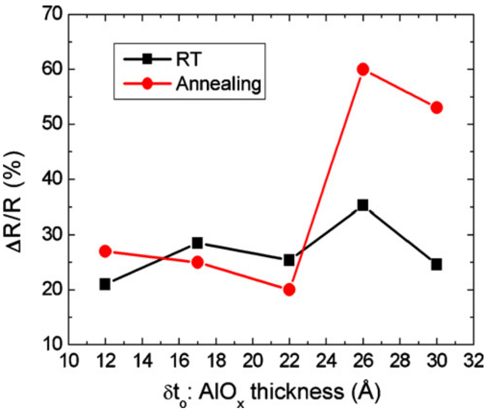

Fig. 2. TMR ratio ($\Delta R/R$) versus thickness (δt_o) of AlO_x layer following RT and field-annealing at 250 °C.

Fig. 3 plots the dependence of magnetostriction on the tunneling barrier AlO_x in the glass/Co(75 Å)/AlO_x(δt_o)/Co(75 Å)/IrMn(90 Å) MTJ following RT and field-annealing at 250 °C. The figure also presents the concave-up feature, with the most negative λ_s value at $\delta t_o = 17$ Å [10]. The λ_s of the MTJ following field-annealing at 250 °C is generally in the range of −20 to −8 ppm, which is lower

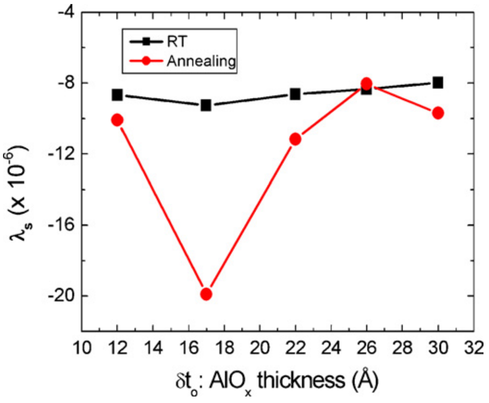

Fig. 3. Magnetostriction λ_s of glass/Co(75 Å)/AlO_x(δt_o)/Co(75 Å)/IrMn(90 Å) junction following RT and field-annealing at 250 °C.

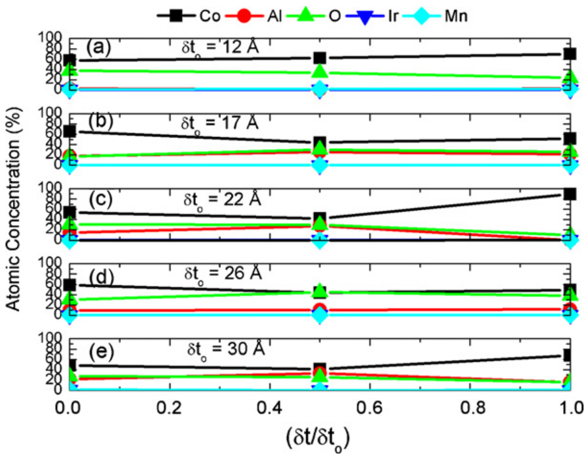

Fig. 4. Atomic concentrations of Co, Al, O, Ir and Mn analyzed across the AlO_x thickness in the Co(75 Å)/AlO_x(δt_o)/Co(75 Å)/IrMn(90 Å) field-annealed junction, where δt_o = (a) 12 Å, (b) 17 Å, (c) 22 Å, (d) 26 Å, and (e) 30 Å.

than that of the RT MTJ, because field-annealing treatment leads to inter-diffusion in the MTJ. Additionally, the λ_s value of an MTJ junction can be controlled in two ways [10]. First, the λ_s of an MTJ can be macro-turned by adjusting the thickness of the two ferromagnetic Co electrodes. Second, λ_s can be micro-tuned by varying δt_o, causing λ_s to exhibit a concave-up characteristic.

Fig. 4 plots atomic concentrations (x_{Co}, x_{Al}, x_O, x_{Ir}, and x_{Mn}) as functions of the normalized ($\delta t/\delta t_o$) position in the AlO_x layer, obtained by EDS analysis across the AlO_x thickness of the MTJ following field-annealing at 250 °C, respectively. According to a previous investigation [19], an MTJ has two λ_s zones: zone (I) is an O-rich CoO film; zone (II) is a Co-rich CoO film. Variations in the thickness of the AlO_x layer, which acts as a diffusion barrier, cause variation in the distributions of concentrations of O and Co during field-annealing. As the δt_o thickness increases from 12 to 17 Å, x_O decreases from 38% to 16% and x_{Co} increases from 57% to 66%. Zone II therefore becomes thicker than zone I, yielding a more negative λ_s value after field-annealing [14]. Conversely, as the thickness δt_o increases from 17 to 22 Å, x_O increases from 16% to 30% and x_{Co} after field-annealing decreases from 66% to 54%. This result indicates that the O-rich effect dominates the λ_s behavior, which is more positive in zone (I) in this situation. As the thickness δt_o increases from 22 to 26 Å, x_O decreases from 30% to 26% and x_{Co} following field-annealing increases from 54% to 59%, suggesting that λ_s is more positive in zone (II) because of the relative abundance of Co. Finally, as the thickness δt_o increases from 26 to 30 Å, x_O increases from 26% to 28% and x_{Co} after field-annealing decreases from 59% to 48%. Zone (I) returns to being O-rich, such that λ_s becomes more negative again. The EDS results demonstrate that the λ_s of field-annealed treated samples tends to be more negative than that of RT samples, potentially revealing that field-annealing at 250 °C may induce the Co-rich inter-diffusion effect. Based on the above mechanisms, λ_s is consistent with the EDS results, as displayed in Fig. 3.

With respect to the consistency between EDS results and TMR ratio (Fig. 2), this investigation focused on the EDS results obtained from the middle of each AlO_x tunneling layer. Fig. 5 plots the atomic concentrations of Co and O. In this figure, the O concentration increases slowly and the Co concentration declines as the δt_o thickness increases from 12 to 30 Å. Fig. 2 plots the TMR ratio, and suggests that the barrier thickness that optimizes the TMR ratio is 26 Å. This result is attributable to the under-oxidation in the AlO_x oxidation process. As the thickness δt_o is increased from 12 to 22 Å, the Co and Al atoms compete to forming an oxidized compound in the AlO_x barrier layer. A very high Co concentration can lead to the formation of a magnetic dead layer, such as CoO or Co_3O_4, which is known to increase the probability of spin-flip scattering, which can reduce the spin polarization of the Co electrode [20]. In under-oxidized barriers, residual paramagnetic Al can depolarize and scatter spin-tunneling electrons, reducing the TMR ratio [21]. The optimal TMR ratio is obtained at when the AlO_x barrier layer is 26 Å thick. According to one study [12], a field-annealing of an MTJ can improve interfacial roughness, reduce the number of defects in the barrier layer and reduce the effective barrier width (S), according to the Simmons formula. Finally, as the barrier thickness increases to 30 Å, under-oxidation associated with lower O oxidation may result in lower TMR ratio. Briefly, the 26 Å optimal AlO_x barrier thickness can be considered as a reference by which other MTJ samples can be regarded as under-oxidized.

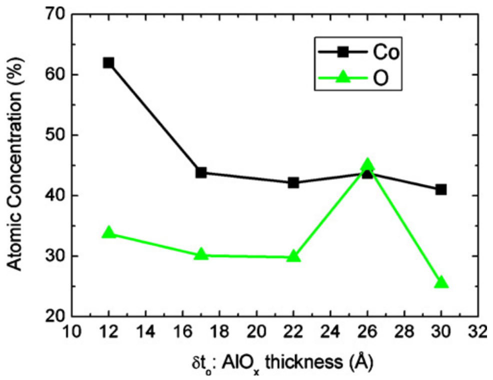

Fig. 5. Atomic concentrations of Co and O analyzed across AlO_x thickness in the middle of each field-annealed junction.

4. Conclusions

In summary, the magnetostriction (λ_s) and tunneling magnetoresistance (TMR) of two MTJ systems were studied at RT and with field-annealing treatment. Field-annealing treatment was found to induce inter-diffusion of mainly Co and O, smoothing the Co/AlO_x and AlO_x/Co interfaces. This fact was verified by cross-sectional HRTEM. The optimal parameters for MTJ systems herein study were an AlO_x thickness of 26 Å, a maximum TMR of 60%, and a minimum λ_s of −8 ppm.

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