Dependence of magnetic anisotropy on MgO sputtering pressure in Co$_{20}$Fe$_{60}$B$_{20}$/MgO stacks

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Abstract. We investigated the dependence of magnetic anisotropy of Ta/Co$_{20}$Fe$_{60}$B$_{20}$/MgO stacks on the Ar partial pressure during MgO deposition, in the range between 0.5 and 15 mTorr. The stacks are studied before and after annealing at 300°C and it is shown that magnetic anisotropy significantly depends on Ar partial pressure. High pressure results in stacks with very low perpendicular magnetic anisotropy even after annealing, while low pressure results in stacks with perpendicular anisotropy even at the as-deposited state. A monotonic increase of magnetic anisotropy energy is observed as Ar partial pressure is decreased.

1. Introduction

Magnetic tunnel junctions (MTJs) with perpendicular magnetic anisotropy (PMA) based on CoFeB/MgO/CoFeB trilayers are being studied for several years for non-volatile and high density data storage applications [1]. The magnetic anisotropy of such multilayers strongly depends on composition, layer thickness, deposition conditions, and annealing temperature; precise tailoring of these parameters must be performed in order to obtain PMA, which originates from the CoFeB/MgO interface [1]. Furthermore, increasing PMA energy is of crucial importance for increasing the thermal stability of MTJ cells and allowing the miniaturization of data storage devices.

In this work, we study the dependence of the magnetic anisotropy of Ta/CoFeB/MgO half-MTJs on the sputtering pressure during MgO deposition. Previous studies of the effect of the sputtering conditions on the properties of CoFeB/MgO-based tunnel junction with in-plane anisotropy (IPA), have shown the importance of Ar pressure during MgO sputtering; it was shown that the smoothness of the CoFeB/MgO interface crucially depends on Ar sputtering pressure, affecting the MTJs’ tunnel magneto-resistance [2, 3, 4]. Here we show that the magnetic anisotropy axis is greatly affected by the Ar partial pressure during MgO sputtering and we determine the pressure range for obtaining PMA.

2. Experimental details

Ta(6 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(1 nm)/MgO(2 nm) multilayers were deposited on Si(100)/SiO$_2$(500 nm) substrates, using ultra-high vacuum magnetron sputtering. The substrates were always kept at room-temperature and were rotating. Direct current power was used for metal deposition (1.5 W/cm$^2$ power density, 3 mTorr Ar working pressure, 0.018 nm/s deposition rate). Radio-frequency power was used for MgO deposition (power density was 10 W/cm$^2$ for all samples deposited). A ceramic MgO target and metallic Ta and Co$_{20}$Fe$_{60}$B$_{20}$ targets were used as source materials. During MgO deposition, the Ar working pressure was between 0.5 and 15 mTorr. All samples were annealed in high-vacuum.
The deposition rate was monitored in-situ by means of a quartz crystal microbalance, calibrated against x-ray reflectivity measurements of test samples. Atomic force microscopy (AFM) imaging was employed for studying the samples’ surface morphology. AFM measurements were performed using a NT-MDT Smena microscope and commercial AFM probes (Bruker PPP-FMR). The magnetostatic characterization was performed using a Quantum Design MPMS SQUID magnetometer.

3. Results and discussion

The multilayer surface morphology was probed by AFM; because of the very low thickness of the MgO layer, the multilayer surface morphology follows the morphology of the CoFeB/MgO interface, which is the focus of this study. The samples are measured before and after annealing at 300°C. The results of the AFM imaging are shown in Figure 1. These results show a clear correlation between the surface morphology and the Ar partial pressure: the root mean square surface roughness increases almost monotonically from 0.40 to 0.57 nm, as Ar pressure increases. This trend is in agreement to previous studies [3] and the effect can be explained by taking into account the higher kinetic energy of the deposited atoms as sputtering pressure decreases. The effect of sputtering pressure is also significant on the deposition rate: higher pressure results in lower deposition rate as sputtered atoms collide with Ar species and are deflected away from the substrate. After annealing, there is an overall increase of surface roughness, although the same trend as before is observed: surface roughness increase from 0.57 to 0.89 nm as Ar pressure increases.

![AFM images](image)

**Figure 1.** Representative AFM images of the multilayer surface morphology after annealing at 300°C. Deposition pressure is (a) 0.5 mTorr, (b) 5 mTorr, and (c) 15 mTorr. (d) Root mean-square surface roughness and deposition rate as a function of Ar partial pressure.

Hysteresis loops have been obtained with the magnetic field applied both perpendicular and in the plane of the samples’ surface. As seen in Figure 2, all annealed samples have PMA, but the anisotropy energy decreases as Ar pressure increases. Figure 2(d) shows the effective anisotropy-CoFeB thickness product variation as a function to the Ar pressure. The effective anisotropy \(k_{eff}\) is experimentally determined from the perpendicular and in-plane hysteresis loops, by comparing the energy difference required to saturate the film along the two directions [5]. As-deposited samples have in-plane anisotropy for Ar pressure higher than 5 mTorr, while PMA with low effective anisotropy energy is obtained for lower sputtering pressure. After annealing, all samples have PMA, with the
effective anisotropy energy increasing as Ar pressure decreases. It should be noted that volume saturation magnetization does not significantly depend on Ar pressure and it is 1020±47 emu/cm$^3$ and 850±39 emu/cm$^3$ before and after annealing, respectively. This decrease is attributed to the interdiffusion of CoFeB and Ta upon annealing, which increases the thickness of the magnetic dead layer present at the Ta/CoFeB interface [5, 6].

Figure 2. SQUID magnetometry hysteresis cycles after annealing at 300°C. MgO films deposited at (a) 0.5 mTorr, (b) 5 mTorr, (c) 15 mTorr. (d) Variation of the effective anisotropy energy-CoFeB thickness product with Ar pressure. The shaded area indicates PMA.

4. Conclusions
We have shown that the magnetic anisotropy axis and the effective anisotropy energy of Ta/CoFeB/MgO half-MTJs significantly depend on MgO sputtering pressure. Low pressure results in multilayers with PMA, even at the as-deposited state. As pressure increases, the effective anisotropy energy decreases and an in-plane easy magnetization axis is favoured. This trend coincides to the increasing MgO/CoFeB interface roughness as the sputtering pressure increases.

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