Perpendicular Magnetic Anisotropy in $\text{Co}_x\text{Pd}_{100-x}$ Alloys for Magnetic Tunnel Junctions

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Abstract- CoFeB/MgO-based perpendicular magnetic tunnel junctions (p-MTJ's) with high anisotropy and low damping are critical for spin-torque transfer random access memory (STT-RAM). Most schemes of making the pinned CoFeB fully perpendicular require ferrimagnets with high damping constants, a high temperature-grown L_{10} alloy, or an overly complex multilayered synthetic antiferromagnet (SyAF). We report a compositional study of perpendicular Co_xPd alloy-pinned $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO}$ based MTJ stacks, grown at moderate temperatures in a planetary deposition system. The perpendicular anisotropy of the Co_xPd alloy films can be tuned based on the layer thickness and composition. The films were characterized by alternating gradient magnetometry (AGM), energy-dispersive X-rays (EDX), and X-ray diffraction (XRD). Current-in-plane tunneling (CIPT) measurements have also been performed on the compositionally varied Co_xPd MTJ stacks. The Co_xPd alloy becomes fully perpendicular at approximately $x = 30\%$ (atomic fraction) Co. Full-film MTJ stacks of Si / SiO_2 / MgO (13) / $\text{Co}_x\text{Pd}_{100-x}$ (50) / Ta (0.3) / CoFeB (1) / MgO (1.6) / CoFeB (1) / Ta (5) / Ru (10), with the numbers enclosed in parentheses being the layer thicknesses in nm, were sputtered onto thermally oxidized silicon substrates and in-situ lamp annealed at 400°C for 5 minutes. CIPT measurements indicate that the highest TMR is observed for the CoPd composition with the highest perpendicular magnetic anisotropy.

Keywords: Perpendicular Magnetic Anisotropy, Perpendicular Magnetic Tunnel Junctions, STT-MRAM, CoPd Alloy

1. Introduction

In recent years a significant portion of spintronics research has focused around CoFeB-MgO-based perpendicular magnetic tunnel junctions (pMTJ's) for spin torque transfer random access memory (STT-RAM).[1-9] Methods for achieving

perpendicular magnetic anisotropy in the pinned layer include using Co/Pd or Co/Pt multilayers as a synthetic antiferromagnet (SyAF) [8,11] or having a fully crystalline L_{10} pinning layer. [7] The multilayered SyAF adds to the complexity of the stack, while the L_{10} layer needs to be deposited or annealed at high temperatures. [12, 13]

CoPd alloys have been investigated in magneto-optics research in the 1990's because of their perpendicular magnetic anisotropy. [14-17] However, there has been very little exploration of CoPd alloys as pinning layers for pMTJ's. The similar alloy CoPt has also been demonstrated to possess similar perpendicular anisotropy and be utilized in a pMTJ[18-22]. In this paper we have studied the properties of CoPd alloys as a function of composition, thickness, growth temperature and post-deposition annealing. We have deposited pMTJ stacks pinned with perpendicular CoPd alloys and characterized them with current-in-plane tunneling (CIPT) measurements.

2. Experimental Details

CoPd alloys were co-deposited from elemental targets onto a variety of seed layers by dc-magnetron sputtering in a planetary SFI Shamrock sputtering system with in-situ rapid thermal annealing capability. The system base pressure was 4×10^{-6} Pa. The CoPd alloys were co-sputtered from elemental targets at 0.8 Pa of Ar, using DC magnetron sputtering. The MgO seed and tunneling barrier layers were deposited using RF magnetron sputtering at 0.26 Pa of Ar. All other layers were DC magnetron sputtered at 0.26 Pa of Ar. The sputter powers for Co and Pd were chosen after EDX

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analysis to determine the composition of the $\text{Co}_x\text{Pd}_{100-x}$ alloys.

All magnetic characterization was performed using a Princeton Alternating Gradient Magnetometer (AGM). [23] X-ray diffraction spectra were taken using a Philips X-Ray diffractometer (XRD) [23] with a Cu $K\alpha$ source. To determine the chemical composition of the films, we measured each sample using electron dispersive spectroscopy (EDS) with an Oxford Xmax 80 mm silicon drift detector [23] mounted on a JEOL 7000 FE-SEM. Current-in-plane- tunneling (CIPT) measurements were performed in a CAPRES [23] system to determine magnetoresistance (MR) of unpatterned MTJ stacks..

CoPd alloy samples were prepared varying both the thickness and composition of the film. In our thickness studies we held the composition constant at equal parts Co and Pd while we varied the thickness of the film. In our compositional studies, the CoPd thickness was held constant at 50 nm, grown on a 13 nm MgO seed layer and capped with 3 nm MgO. Post-deposition annealing was performed in-situ using rapid thermal annealing at 400°C for 5 minutes. The samples were allowed to cool in vacuum. Our experiments show that Ta/Pt and Ta/Pd function equally well as seed layers.

Perpendicular magnetic tunnel junction stacks were deposited to explore the use of a CoPd alloy to pin the CoFeB layer perpendicular. In a series of pMTJ's, the CoPd composition was varied. The layer structure of the stacks was Si / SiO_2 / MgO (13) / $\text{Co}_x\text{Pd}_{100-x}$ (50) / Ta (0.3) / CoFeB (1) / MgO (1.6) / CoFeB (1) / Ta (5) / Ru (10), with the numbers enclosed in parentheses being the layer thicknesses in nm. These stacks were in-situ rapid thermally annealed at 400°C for 5 minutes after deposition.

3. Results and Discussion

Figure 1 (a) and (b) show the effect of thickness variation on the perpendicular anisotropy of the $\text{Co}_{50}\text{Pd}_{50}$ film annealed after deposition at 450 °C. At lower thicknesses the films are in-plane. The perpendicular anisotropy increases with thickness and the film becomes fully perpendicular at 50 nm. The sample structure was Si (100) / MgO (10) / $\text{Co}_{50}\text{Pd}_{50}$ (x) / anneal (450°C) / MgO (3), where (x) = 10, 20, 35, 50, 75 and 100, with the numbers enclosed in

parentheses being the layer thicknesses in nm. From the normalized M-H loops as shown in Figure 1, it is evident that the nucleation field increased with increased thickness in the out-of- plane loops.

FIG 1 Here

Further experimentation showed that the sample can be deposited at room temperature as long as the in-situ post-deposition annealing is performed. As this simplified the sample processing and potentially would make it more viable for industrial applications, we eliminated the pre-heating step and only performed the in-situ post-annealing step

If we hold thickness constant, at 50 nm, and vary the composition of the Co and Pd we see interesting behavior. As we decrease the percentage of Co, we see that the loops shift from a bowtie shape to squarer loops. The normalized hysteresis loops over various compositions are presented in Figures 2(a) and 2(b). As these graphs can be hard to quantify visually, we have extracted the important parameters and plotted them in Figure 3.

FIG 2 Here

In Figure 3(a) we plot the remanent magnetization (M_r) as a proportion of the saturation magnetization (M_s). This is related to the squareness of the M-H loop. As one can see, M_r/M_s increases as we decrease the Co composition until we pass 22 % Co (atomic fraction), at which point it drops, the highest value being 0.9. This shows quite clearly that the alloy is becoming more perpendicular as we decrease the amount of Co in the system. Once we pass a critical point, the alloy acts more like pure Pd.

The coercivity H_c vs. composition is plotted in Figure 3(b). A sharp rise in the coercivity is seen at about 30% Co. This increase in coercivity arises as the system transitions from switching as independent domains to switching uniformly. The saturation magnetization (M_s) is plotted vs. Co% in Figure 3(c) and is seen to be a straight line in relationship to the atomic percentages. This decrease occurs because we are removing ferromagnetic Co atoms and replacing them with paramagnetic Pd. The anisotropy field (H_k), which determines the amount of field needed to switch the sample was found by determining the

saturation field (H_s) using the 95% rule, which is the applied field that induces a magnetization that is 95% of saturation, and equation 1 below. H_k is plotted vs. Co composition in Figure 3(d) which correlates well with the M_r/M_s plot. In Figure 3(e) we plot the anisotropy constant using equation 2. The highest K_u is at 22.7% Co composition, which agrees well with Figures 3(a) and 3(c).

$$H_k = H_s - 4\pi M_s \quad (1)$$

$$Ku = \frac{M_s H_k}{2} \quad (2)$$

FIG 3 Here

As shown in the X-ray diffraction spectra in Figure 4, the crystal structure of the film was determined to be fcc with a clear (111) peak observable in all samples at roughly 42° , [24,25] while 39.4% Co to 14.9% Co show a weak (200) peak at roughly 48° . [24] The shifting of the major peak to the left as the Pd concentration increases may be due to increasing strain in the lattice as the larger Pd atoms substitute for the Co. Similar shifts were observed by N. Nozawa, et al. [25]

FIG 4 Here

Analysis of our XRD spectra shows that the (111) peak position gradually shifts as we adjust the composition as shown in figure 5 (a). The (111) peak is also well developed enough that we can extract the full width at half maximum, shown in figure 5 (b). This allows us to use the Sherrer equation to estimate the grain size,²⁶ which is shown in figure 5 (c). Lastly we estimated the lattice constant based on the peak position, which is shown in figure 5 (d). As one can see the lattice increases as we add larger Pd atoms.

FIG 5 Here

So far we have only shown thickness variations at $\text{Co}_{50}\text{Pd}_{50}$ alloy ratio. In figure 6 we investigate thickness variations at $\text{Co}_{25}\text{Pd}_{75}$ composition, using the stack Si / SiO_2 / MgO (13) / $\text{Co}_{25}\text{Pd}_{75}$ (x) / Ta (5), where (x) equals (10), (20), (30), (40), and (50), with the numbers enclosed in

parentheses being the layer thicknesses in nm. This shows that the system retains its perpendicular anisotropy down to 20 nm. The squareness of the loops seems to improve down to 30 nm and starts to drop off again.

FIG 6 Here

Magnetic tunnel junction stacks were deposited as a function of CoPd alloy composition as follows: Si / SiO_2 / MgO (13) / $\text{Co}_x\text{Pd}_{100-x}$ (50) / Ta (0.3) / $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$ (1) / MgO (1.6) / $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$ (1) / Ta (5) / Ru (10), where x is the atomic percentage of Co and the numbers enclosed in parentheses are the layer thicknesses in nm. In Figure 7(a) we show the hysteresis loops of the magnetic tunnel junctions. These hysteresis loops correlate with what we observe in Figure 2. Our CIPT measurements are shown in Figure 7(b). As we can see, the maximum MR correlates with the maximum K_u values seen in Figure 3(e), at 25% Co. Further refinement of the MTJ trilayer, particularly the MgO barrier layer, will undoubtedly improve the MR.

FIG 7 Here

4. Conclusions

We have explored CoPd over various ratios of Co to Pd. We have found that it has the highest perpendicular magnetic anisotropy at 20-25% (atomic fraction) Co. Further, we have found that CoPd is effective at perpendicular pinning of the CoFeB layer of a MTJ. This means that CoPd has the potential to function as a simple replacement for other more complex pinning schemes.

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Figures:

Figure 1. Normalized Hysteresis loop of $\text{Co}_{50}\text{Pd}_{50}$ over various thickness; (a) In-Plane (b) Out-of-plane.

Figure 2. Normalized hysteresis loops over various Co compositions fixed at 50nm; RTA 400°C for 5 min (a) In-Plane (b) Out-of-Plane.

Figure 3. (a) M_r/M_s (b) Coercivity (c) Saturation Magnetization (d) Anisotropy Field (e) Anisotropy Constant; over variation of Co composition

Figure 4. X-ray diffraction spectra of CoPd vs. variation of Co composition, Cu $K\alpha$ source

Figure 5. X-ray diffraction spectra analysis.

Figure 6. Hysteresis loop of $\text{Co}_{25}\text{Pd}_{75}$ over various thickness

Figure 7. (a) Hysteresis loops of all MTJ stacks (b) CIPT MR% V. Co% at.%.