Pseudo spin valves based on $L_10$ (111)-oriented FePt and FePtCu fixed layer with tilted anisotropy

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Abstract. We demonstrate a series of pseudo-spin-valve structures based on $L_10$ (111)-oriented FePt and FePtCu with tilted magnetocrystalline anisotropy. Highly ordered (111)-oriented $L_10$ FePt and $L_10$ FePtCu with large anisotropy is achieved by optimizing the Cu content. Magnetoresistance (MR) up to 5% has been obtained by $i$) optimizing the fixed-layer growth using different underlayers, $ii$) enhancing the interface spin polarization using thin CoFe at the Cu interfaces, and $iii$) adjusting the Cu spacer thickness. The substantial MR realized with tilted fixed layer magnetization is an important prerequisite for the realization of tilted polarizer Spin Torque Oscillators (STO) or Spin-Transfer Torque Magnetoresistive Random Access Memories (STT-MRAM).

1. Introduction

Since the spin-transfer torque effect (STT) was theoretically described in 1996 [1,2] and experimentally verified in 2000 [3], it has been extensively investigated due to its great potential in next-generation magnetoresistive random access memory (MRAM), magnetic race-track memory, and spin torque oscillators [4]. Prior to the commercial application of STT-related devices, there are still a few important problems needed to be overcome, such as the high critical current density for switching or domain wall displacement, or the need for large external magnetic fields in STOs. Recently, micromagnetic simulations have showed that a tilted spin polarizer in spin valves based or magnetic tunnel junctions based nano-spintronic devices, might reduce the switching time and the critical switching current density in STT-MRAM [5,6]. Also, we have proposed an improved design for STOs based on a tilted spin polarizer, and demonstrated in simulations that it would be capable of zero-field operation while keeping a suitable output signal [7]. These simulation works have clearly demonstrated that the tilted spin polarizer can be advantageous in comparison to both in-plane and perpendicular spin polarizers.

In this paper, we report on a systematic study of pseudo spin valves based on $L_10$ (111)-oriented FePt and $L_10$ (111)-oriented FePtCu spin polarizers with tilted magnetocrystalline anisotropy. The highly ordered $L_10$ phase in FePt is achieved by alloying with Cu, which significantly lowers the required deposition and annealing temperatures. We demonstrate as high as 5% MR through $i$) optimized ultra-smooth growth of $L_10$ FePt and $L_10$ FePtCu using different underlayers, $ii$) enhanced interface spin polarization using at thin CoFe layer at the Cu interfaces, and $iii$) tuning the Cu spacer thickness.
2. Experiments

All films are deposited on thermally oxidized Si substrates using a magnetron sputtering system. $L_{10}$ Fe$_{53}$Pt$_{47}$ (FePt) and (Fe$_{53}$Pt$_{47}$)$_{85}$Cu$_{15}$ (FePtCu) films with 20 nm thickness are fabricated by co-sputtering elemental Fe, Pt and Cu at a nominal substrate temperature of 700 °C, subsequently followed by an in-situ anneal at the same temperature for 10 min. Ta or Ta/Pt underlayers are deposited at the same temperature as the FePt and FePtCu layers. A Co$_{50}$Fe$_{50}$ (CoFe) spin enhancing layer and the Permalloy (NiFe) free layer, as well as the Ta capping layer are all sputtered at room temperature. Magnetic properties are characterized using a Physical Property Measurement System (PPMS) equipped with a Vibrating Sample Magnetometer (VSM) with a maximum field of 90 kOe and an alternating-gradient magnetometer (AGM) with a maximum field of 14 kOe. Surface roughness is studied using atomic force microscopy (AFM). Crystallographic structures are investigated by x-ray diffraction (XRD) with Cu K$_\alpha$ radiation in a symmetric scan geometry. Current-in-plane (CIP) electron transport properties are characterized by a standard 4-point tester with the current orthogonal to the magnetic field.

3. Results and discussion

Figure 1 displays the XRD patterns of FePt and FePtCu films deposited on different underlayers. While all films show (111)-preferred orientation, regardless of type of underlayer, the exact peak location varies. In particular, they are located at 40.87°, 40.92°, 40.90°, 41.15° for FePt on SiO$_2$ underlayer, on SiO$_2$/Ta underlayer, and on SiO$_2$/Ta/Pt underlayer as well as FePtCu on SiO$_2$/Ta/Pt underlayer, respectively. In other words, the peak is gradually approaching the expected 41.08° position of the (111) peak of fully-ordered FePt according to the JCPDS card (PDF No.43-1359). This indicates that $L_{10}$ phase chemical long-range ordering degree is increased. The slight shift towards angles greater than 41.08° is ascribed to the Cu dopant, which gives FePtCu a slightly smaller $c$ lattice parameter [8]. As shown in Fig. 1 (a), a superlattice FePt (001) peak appears, suggesting the formation of the $L_{10}$ phase, but the chemical ordering degree is still low due to a mixture of (200) and (002) peaks. Also, this is consistent with the shifted position of the (111) peak. However, in Figs. 1 (b), (c), and (d) the superlattice peaks, such as (001) or (110), are not observed for the present $\theta \sim 2\theta$ specular x-ray diffraction scanning configuration (i.e. diffraction planes parallel to the film surface) due to space limitation. Meanwhile, the underlayers greatly improve the $L_{10}$ (111) preferred orientation. Consequently, the magnetocrystalline easy-axis of the ordered FePt and FePtCu films is expected to be tilted out-of-plane at an approximate angle of 36° with respective to the film plane, because the magnetocrystalline easy axis of $L_{10}$ FePt and $L_{10}$ FePtCu is along the $[001]$ direction (i.e. here [010] direction is placed in approximate 36° cone plane tilted from the film plane. Note that magnetocrystalline anisotropy with $\sim 10^7$ erg/cc dominates in hard $L_{10}$ FePt and FePtCu).

In addition, it is found that symmetric satellite peaks are located on both sides of the (111) peak, signifying that both the FePt and FePtCu films have a very smooth surface when appropriate underlayers are used. This is corroborated by AFM measurements as shown in the insets of Fig. 1, where FePt deposited directly on SiO$_2$ exhibits the roughest surface (the inset of Fig. 1(a)) with $\sim$1.8 nm root mean square (rms) roughness, but the use of a 6-nm-thick Ta underlayer drastically reduces this to only 0.8 nm, and further to 0.7 nm when a very thin 3-nm-thick Pt is inserted in between Ta and FePt. Furthermore, the FePtCu film on optimized underlayer of Ta/Pt bilayer shows a reasonably good surface roughness of 1.3 nm rms.

Figure 2 reveals in-plane and out-of-plane hysteresis loops measured by PPMS-VSM under ±90 kOe field and here the loops are zoomed in to ±30 kOe for a clearer view. It is found that FePt directly deposited on SiO$_2$ underlayer exhibits 1.2 kOe in-plane coercivity and 1.3 kOe out-of-plane coercivity but in-plane remanence is larger than out-of-plane remanence. However, When introducing Ta as an underlayer for FePt growth, the in-plane coercivity is dramatically increased to 6.8 kOe and the out-of-plane one to 5.7 kOe. This might result from improvement
of chemical long-rang ordering degree, in accordance with XRD results. Nevertheless, further introducing a thin Pt on the Ta underlayer, the coercivity is slightly reduced. The reduction might originate from Pt diffusion from the bottom, leading to a Pt-rich composition at the underlayer interface with a reduced chemical ordering, consistent with the XRD results. For the Cu alloyed FePt grown on the Ta/Pt underlayer, the coercivities are greatly increased to 12.3 kOe and 12.8 kOe for in plane and out of plane, respectively, as expected from the higher chemical ordering of L1₀ phase in FePtCu. It is noteworthy that all loops show greater in-plane remanence than out-of-plane remanence in good agreement with a 36° magnetocrystalline anisotropy.

![Figure 1](image1.png)

**Figure 1.** XRD patterns of (a) SiO₂/FePt/Ta; (b) SiO₂/Ta/FePt/Ta; (c) SiO₂/Ta/Pt/FePt/Ta; (d) SiO₂/Ta/Pt/FePtCu/Ta. Shown in the insets are atomic force microscopy images of FePt or FePtCu deposited on related underlayer(1×1 μm²). The rms roughness values are indicated in the images.

![Figure 2](image2.png)

**Figure 2.** In-plane and out-of-plane PPMS-VSM hysteresis loops of (a) SiO₂/FePt/Ta; (b) SiO₂/Ta/FePt/Ta; (c) SiO₂/Ta/Pt/FePt/Ta; (d) SiO₂/Ta/Pt/FePtCu/Ta.

Figure 3 shows CIP magnetoresistance curves of the pseudo spin valves. In the case of a FePt fixed layer, i.e. no CoFe spin polarization enhancing layers, the FePt/Cu/NiFe trilayer shows only 0.88% MR. The resistance peaks at a low field of ~50 Oe, corresponding to the free layer switching. This indicates that, while low, the observed MR still mainly originates from giant magnetoresistance (GMR). When we introduce two very thin CoFe spin polarization enhancing layers located at both sides of the Cu spacer layer, MR increases significantly to 3.38%. MR is further increased to 3.85% when we employ a Ta underlayer for improved FePt growth, and to 4.13% when the interface roughness is further reduced using a Ta/Pt underlayer. We hence conclude that in these spin valves, and in the investigated roughness region, roughness is detrimental to high MR. This trend also holds true when we alloy FePt with Cu. In Fig. 3 (e) we measure MR of 3.10% for an FePtCu fixed layer with 1.3 nm rms roughness. In an attempt to remedy this drop in MR, we investigate the impact of the Cu spacer thickness and found an optimum thickness around 2.4 nm for which MR approaching 5% can be achieved, as shown in Fig. 3(f).
4. Conclusion
In summary, we have demonstrated MR above 4% in FePt based spin valves and MR approaching 5% in FePtCu based spin valves, all with strong tilted magnetocrystalline anisotropy. We find that Cu alloying can dramatically improve both the chemical ordering of the (111) oriented $L_1_0$ phase and the coercivity of FePtCu layers. On the other hand, we find that the increased ordering is accompanied by a somewhat rougher film surface and a corresponding reduction in MR. After optimizing the Cu spacer thickness to reach almost 5% MR we however believe that Cu alloying can strike a reasonable compromise between full chemical ordering, large coercivity, film smoothness, and high MR in spin valves with tilted spin polarization.

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