Study on the dual-synthetic antiferromagnetic property using the Co$_2$FeAl Heusler electrodes

D L Zhang, X G Xu *, Y Wu, X Q Li, J Miao and Y Jiang *

State Key Laboratory for Advanced Metals and Materials, School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China

E-mail: yjiang@ustb.edu.cn; xgxu@ustb.edu.cn.

Abstract. In this paper, we present the experimental results of dual-synthetic antiferromagnets (DSyAFs) with Co$_2$FeAl (CFA) Heusler electrodes. It is shown that when the thicknesses of Ru layers are (0.45, 0.65) and (0.45, 1.00) (in nm), the CFA-based DSyAFs have a strong synthetic antiferromagnetic coupling among three CFA layers at room temperature, with a large saturation magnetic field $H_s$ of ~11000 Oe, a low saturation magnetization $M_s$ of ~708 emu/cm$^3$ and a switching field $H_{sw}$ of ~2.0 Oe, respectively. It is exciting that the CFA-based DSyAFs have an excellent thermal stability up to 400 °C. Therefore, the CFA-based DSyAFs are favourable for applications in future spintronic devices.

1. Introduction
Spintronic devices based on spin valves (SPVs) or magnetic tunnel junctions (MTJs) such as magnetic random access memory (MRAM) and magnetic logic circuit have been considered as promising candidates for the next generation ultrahigh density magnetic storage devices [1-2]. As chief components in the SPVs or MTJs, synthetic antiferromagnets have attracted considerable attention and have been widely researched. Half-metallic ferromagnets (HMFs) have a band gap in the minority spin in band structure and theoretically exhibit a 100% spin polarization at the Fermi level [3]. Especially, the Co-based full-Heusler alloys with a chemical formula of Co$_2$YZ (Y = Fe, Mn; Z = Al, Si, Ge, Ga, Sn) show excellent half-metallic properties and have been considered as promising materials in spintronics devices [4-5]. Magnetostatic interaction between pinned and free layers in SPVs becomes an important problem and attracts great attentions. Synthetic antiferromagnet (SyAF) provides a method to resolve the problem due to its closed magnetic flux configuration and low stray field [6-7].
In recent years, researchers have made continuous efforts to find new synthetic antiferromagnets or optimize SyAF in order to achieve excellent antiferromagnetic coupling properties of large saturation field (Hₛ), low saturation magnetization (Mₛ), small coercivity (Hc), and good thermal stability. Due to the high spin polarization and Curie temperatures, Co-based full-Heusler alloys are ideal ferromagnetic materials used in SPVs or MTJs and have attracted much interest [8]. If the Heusler alloys can be applied in SyAF structure, it will be possible to make “all Heusler” SPVs or MTJs and get much higher giant magnetoresistance (GMR) or tunnel magnetoresistance (TMR). Xu et al [9] have firstly reported a CFA-based SyAF structure which shows a strong antiferromagnetic coupling between two CFA layers at room temperature (RT). However, the antiferromagnetic coupling can only maintain up to 150 °C, indicating poor thermal stability.

Therefore, we investigate the CFA-based dual-synthetic antiferromagnet (DSyAF) structure in order to obtain excellent synthetic antiferromagnetic properties and improve thermal stability.

2. Experiment

In this paper, the CFA-based DSyAFs with a stack of Ta(4)/CFA(5)/Ru(x)/CFA(3)/Ru(y)/CFA(5)/Ta(4) (x=0.45, y=0.45; x=0.45, y=0.65; x=0.45, y=1.00; x=0.65, y=1.00; x=1.00, y=1.00) (in nm) were deposited on a Si (100) substrate using dc magnetron sputtering with an argon pressure of ~0.5 Pa. The base pressure of chamber was better than 2.0×10⁻⁵ Pa. A 100 nm CFA monolayer and CFA-DSyAF samples were fabricated at RT. In order to study the crystalline structure and thermal stability, all the samples were annealed at 100 °C, 200 °C, 300 °C, and 400 °C for 1 hour in a vacuum furnace with a pressure lower than 5×10⁻⁵ Pa, respectively. Magnetic properties of the samples were measured by alternating gradient magnetometer (AGM), and the crystalline structure of CFA monolayer was determined by X-ray diffraction (XRD) at RT.

3. Results and discussion

Figure 1(a) shows the magnetization curves of the CFA-based DSyAFs. The results show that the CFA-based DSyAFs (x=0.45, y=0.45, 0.65 and 1.00) have a strong antiferromagnetic coupling among three CFA layers. When the thicknesses of the two Ru layers are x=0.45 nm and y=0.45 nm, the saturation field Hₛ, the saturation magnetization Mₛ and the switching field Hₛ are ~6000 Oe, 572 emu/cm³, and 3.6 Oe, respectively. When x=0.45 and y increases from 0.45 nm to 1.00 nm, Hₛ increases from ~6000 Oe to ~11000 Oe, with an increasing Mₛ from 572 emu/cm³ to 708 emu/cm³ [as shown figure1(a)] and a decreasing Hₛ from 3.6 Oe to 2.0 Oe [as shown figure1(b)]. So it is obvious that the CFA-based DSyAFs (x=0.45 y=0.65 and 1.00) have an excellent synthetic antiferromagnetic property.
Because the middle CFA layer is thinner than the others, it allows the antiferromagnetic coupling arising from the two Ru layers to be superposed on one another to enhance the overall coupling strength, thus gaining the largest saturation field $H_s$ about ~11000 Oe compared with the $H_s$ value of the CFA-based SyAF of only ~5000 Oe. The CFA-based DSyAF ($x=0.45$, $y=1.00$) has a saturation magnetization of ~708 emu/cm$^3$, which is lower than those of the Co$_{90}$Fe$_{10}$-based DSyAF (~870 emu/cm$^3$) and SyAF (~1200 emu/cm$^3$) [10]. The reason is that the $M_s$ of CFA (~1000 emu/cm$^3$) [9] is smaller than that of Co$_{90}$Fe$_{10}$ (~1300 emu/cm$^3$). In addition, the switching field $H_{sw}$ about ~2.0 Oe of the CFA-based DSyAF ($x=0.45$, $y=1.00$) is lower than that of the CFA-based SyAF (~4.3 Oe), especially much lower than those of the Co$_{90}$Fe$_{10}$-based DSyAF (~150 Oe) and SyAF (~70 Oe). This is because that the $H_c$ of CFA (~5.0 Oe) is much smaller than that of Co$_{90}$Fe$_{10}$ (~57 Oe) [10].

In order to investigate the thermal stability of the CFA-based DSyAFs ($x=0.45$, $y=0.65$; $x=0.45$, $y=1.00$), the samples were annealed at 100 °C, 200 °C, 300 °C, and 400 °C in a vacuum furnace. The M-H loops of the as-deposited and annealed CFA-based DSyAFs ($x=0.45$, $y=0.65$; $x=0.45$, $y=1.00$) are presented in Figure 3 (a~b). The results show that the $H_s$ and $M_s$ of CFA-based DSyAF ($x=0.45$, $y=0.65$) are about ~4492 Oe and ~510 emu/cm$^3$ with the annealing temperature 400 °C as shown in figure 2(a). It indicates that the CFA-based DSyAF has an excellent thermal stability up to 400 °C, despite the antiferromagnetic coupling strength is weakened by the increasing annealing temperature. In addition, the $H_s$ and $M_s$ of CFA-based DSyAF ($x=0.45$, $y=1.00$) are about ~2510 Oe and ~701 emu/cm$^3$ with annealing temperature increasing to 400 °C. It also indicates that the CFA-based DSyAF ($x=0.45$, $y=1.00$) has the good thermal stability up to 400 °C as shown figure 2(b).
Figure 2 (a). M-H loops of CFA-DSyAF (0.45; 0.65). (b). M-H loops of CFA-DSyAF (0.45; 1.00).

We studied the crystalline structure of CFA monolayer at different annealing temperatures. Figure 3 shows the XRD patterns for the annealed CFA films. As for the curves of 300 °C annealed CFA films, only (220) peak of the full-Heusler alloy can be detected, indicating an A2-disordered structure. When the annealing temperature increases to 400 °C, there emerges (200) peak of the full-Heusler alloy in the XRD pattern, which indicates that the B2-ordered structure can be obtained after annealing at 400 °C. So the CFA-based DSyAFs with the high spin polarized B2-ordered structure perform excellent synthetic antiferromagnetic properties and thermal stability.

Figure 3. XRD patterns of 100 nm CFA film.

In addition, we have also studied the correlation between the $H_s$ ($M_s$ and $H_c$) and the annealing temperatures. As shown in Figure 4(a), the $H_s$ decreases from ~13237 Oe to ~4492 Oe in the CFA-based DSyAF($x=0.45, y=0.65$) and from ~12548 Oe to ~2510 Oe in the CFA-based DSyAF($x=0.45, y=1.00$) with temperature increasing from 25°C to 400 °C. The saturation magnetization $M_s$ increases gradually from ~708 emu/cm³ to ~858 emu/cm³ at Ta=100 °C, then decreases slowly to ~701 emu/cm³ at T=400 °C in the CFA-based DSyAF ($x=0.45, y=1.00$), and the $M_s$ of the CFA-based DSyAF ($x=0.45, y=0.65$) decreases slowly from ~680 emu/cm³ to ~510 emu/cm³ with temperature increasing from 25 °C to 400 °C as shown in figure 4 (b). For the coercivity $H_c$, the CFA-based DSyAF ($x=0.45, y=0.65$ and 1.00) have a small $H_c$ about 2.0 Oe at RT. With the temperature increasing from 25 °C to 400 °C,
the $H_s$ of the CFA-based DSyAF ($x=0.45$, $y=0.65$) increases slowly from ~2.0 Oe to ~14.7 Oe. However, the $H_s$ of the CFA-based DSyAF($x=0.45$, $y=1.00$) increases gradually from ~2.0 Oe to 6.8 Oe under 300 $^\circ$C, and then decreases to ~1.5 Oe at $T_a=400$ $^\circ$C as shown in figure 4 (c).

Figure 4. (a) $H_s$-$T_a$ curves of CFA-DSyAF, (b) $M_s$-$T_a$ curves of CFA-DSyAF, (c) $H_s$-$T_a$ curves of CFA-DsyAF.

The CFA-based SyAF ($x=0.45$) loses antiferromagnetic property after annealing at 200 $^\circ$C [9]. The Co$_{90}$Fe$_{10}$-based DSyAF ($x=0.45$, $y=1.00$) has a low $H_s$ about ~3400 Oe but a high $M_s$ about ~1000 emu/cm$^3$ after annealing at 300 $^\circ$C[10]. Therefore, the CFA-based DSyAFs($x=0.45$, $y=0.65$ and 1.00) have an excellent synthetic antiferromagnetic property and the best thermal stability among all studied SyAFs and DSyAFs candidates, though its antiferromagnetic coupling is weak after 400 $^\circ$C annealing. Accordingly, the CFA-based DSyAF has an enhanced thermal stability up to 400 $^\circ$C and a low $M_s$, comparing with other SyAFs and DSyAFs, which will do favor to ultrahigh storage density. Therefore, the CFA-based DSyAF will have a bright future in spintronic devices due to its excellent thermal stability and the high spin polarized B2-ordered structure of CFA films.

4. Conclusion

We have successfully fabricated the CFA-based DSyAF structures having a stack of CFA/Ru/CFA/Ru/CFA. Compared with all studied SyAFs and DSyAFs candidates, the CFA-based DSyAF has a high saturation magnetic field $H_s$, a low saturation magnetization $M_s$, and a low switching field $H_{sw}$. The enhanced thermal stability up to 400 $^\circ$C of CFA-based DSyAFs allows the phase transformation of CFA to high spin polarized B2-ordered phase.
According to the experimental results, the CFA-based DSyAF is a promising structure for application in spintronics devices.

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