

Effect of Thickness on Magnetic Dipolar and Exchange Interactions in SmCo/FeCo/SmCo Thin Films

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Abstract

SmCo/FeCo/SmCo trilayer was deposited with two different thickness configurations for soft phase (FeCo); 50 nm/10 nm/50 nm and 50 nm/25 nm/50 nm were deposited on Si (111) substrate and Ta (50 nm) seed layer by RF magnetron sputtering in a pressure, p , of 30 - 35 m Torr. After deposition the films were annealed under Ar atmosphere at temperature T equal to 923 and 973 for different times followed by quenching in water. X-ray diffraction patterns were obtained to identified phase presents and calculate average crystallite size. To study the effect of configuration thickness in soft phases, DC magnetic measurements were carried out; the measurements were done in the temperature interval of 300 - 50 K. Hysteresis loops collected at low temperatures exposed an increment in coercivity with the decrease of T and at same time, presented a "knee" in the second quadrant of the demagnetization curve, which suggests that the inter-layer exchange coupling becomes less effective, being more evident for sample with 50 nm/25 nm/50 nm thickness. Moreover, $\delta M(H)$ plots were calculated from magnetic measurements at three different temperatures, T , equal to 300, 150 and 50 K, which corroborates that the dipolar interactions became stronger when thickness of soft phases increases. Finally, the thickness effect is attributed to the SmCo₅ phase magnetocrystalline anisotropy constant, which is responsible for the exchange coupling length.

Keywords

Exchange Interactions, Dipolar Interaction, Anisotropy

1. Introduction

Kneller and Hawig [1] first introduce an exchange spring composite magnet consisted of hard and soft magnets. The hard magnetic phase provides a high coercive force while the soft phase offers a high magnetization. Then, Skomski and Coey [2] predicted a giant energy product $(BH)_{\max}$ with theoretical value of 120 MGOe using this exchange spring. Since the magnetic properties and the degree of exchange coupling are strongly dependent on the microstructural parameters, phase distribution, volume and crystallite size. The nanocomposite multilayer films can be prepared by the technique such melt spinning [3]-[5], mechanical milling [6]-[8], sputtering [9]-[12] and nanoparticle assembly [13]. Nanocomposite multilayer films prepared by sputtering are of the state of the art in permanent magnets and, its interest is not only for understanding the mechanism of nanocomposite magnets but also for developing the next generation of magnets [14].

For the last two decades, many researchers focused their research on the exchange coupling in the interface between the hard and soft phases [15], the temperature dependence of the exchange spring bilayers, the effect of inter-diffusion at the interface on exchange coupling and the effect of controlled composition interface on exchange spring magnet [16]-[22].

In this paper, we report the study of effect thickness in magnetic dipolar and exchange interaction in the trilayer SmCo/FeCo/SmCo. It was found a strong dependence of soft layer thickness in the exchange and dipolar interactions at low temperature measurements.

2. Experimental

SmCo/FeCo/SmCo thin films were deposited on Si (100) substrate by RF magnetron sputtering system with a base pressure of 5×10^{-6} Torr. SmCo and FeCo were deposited by SmCo target composition and FeCo target composition. A Ta underlayer and Ta cap layer also were deposited by RF magnetron sputtering Ta target (purity of 99.95%). Ar pressure was kept at range of 30 - 35 m Torr. Two different thickness configurations for soft phase (FeCo): 50 nm/10 nm/50 nm and 50 nm/25 nm/50 nm were deposited; the thickness of Ta, SmCo and FeCo layer were controller by Inficon microbalance. The as-deposited film were annealed in vacuum at different temperature T equal to 923 K for 60 min and 973 K for 15 min followed by quenching in water. X-ray diffraction (XRD) patterns were obtained using a Panalytical X'Pert MPD diffractometer with Cu-K α radiation in a 2θ ranging from 30° - 60° with a step size of 0.008° and time for step 30 s. Magnetic hysteresis loops were measured on a Quantum Design VersaLab vibrating sample magnetometer (VSM) in fields up to 30 kOe at temperature, T, ranging from 300 to 50 K.

3. Results and Discussion

Figure 1 shows XRD pattern obtained for thickness variation in the soft phase from 10 to 25 nm and annealing temperature from 923 K for 60 minutes to 973 K for 30 minutes, respectively. To understand the magnetic behavior of multilayer system just FeCo soft layer thickness changed, SmCo hard layer thickness was constant to 50 nm. In DRX SmCo and FeCo diffraction peaks are very small due the formation of most SmCo and FeCo clusters were amorphous associated with few small crystallites [23]. All phases in samples were identified with SmCo₅ (PDF2-00-027-1122), Fe₆₅Co₃₅ (PDF2-00-048-1817), Ta (PDF2-00-002-1104), TaO₂ (PDF2-00-019-1297), Ta₂O₅ (PDF2-00-018-1304). The as-deposited sample was amorphous. Therefore, it is evident that as heat treatment was carried out, the (111) peak of the SmCo₅ appears and also the (110) peak of Fe₆₅Co₃₅.

The M-H loops of SmCo/FeCo/SmCo samples annealed at T = 923 K for 60 minutes and T = 973 K for 30 minutes were measurement by VSM with a magnetic field of 30 kOe applied in substrate plane direction. **Figure 2** shows the hysteresis loops of SmCo/FeCo/SmCo films with different thickness for soft phase, annealed at different temperature. Samples annealed at 973 K for 30 minutes and 923 K for 60 minutes were deposited with 10 and 25 nm for FeCo layer, respectively. The VSM measurement temperature was in the range between 300 and 50 K. The demagnetization curve at 300 K has a smooth convex profile that, according to Kneller and Hawig, correspond to a fully exchange coupled nanocomposite. Meanwhile, as temperature decrease, the sample with FeCo layer with 10 nm thickness exhibits a little “Knee” in the second quadrant and the “Knee” for sample with FeCo layer with 25 nm thickness is much more pronounced. This effect has been interpreted as an exchange decoupling due to the difference in the thickness of FeCo layer [23] [24].

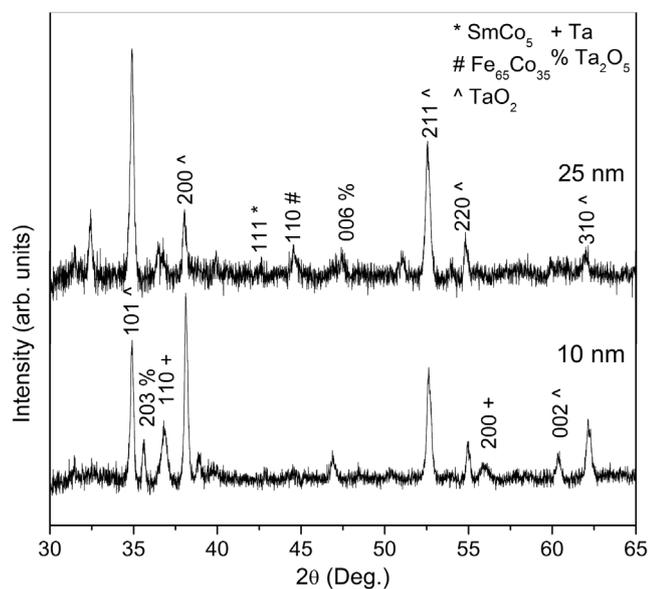


Figure 1. XRD of SmCo/FeCo/SmCo films with different thickness and heat treatment.

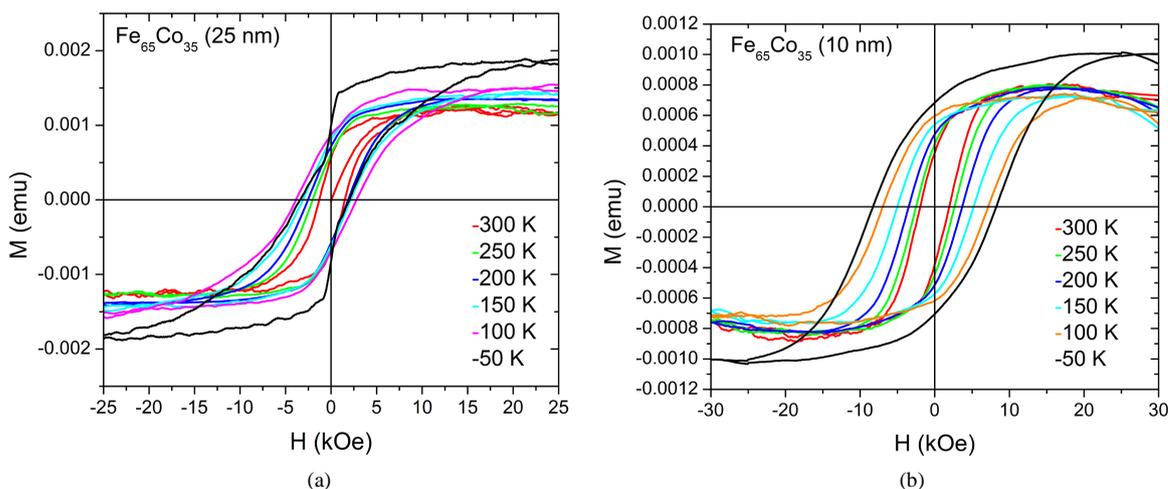


Figure 2. Hysteresis loop of SmCo/FeCo/SmCo films measured in low temperature range $T = 300 - 50$ K.

Figure 3 shows maximum magnetization, M_r , remanence, and M_{\max} , remanence to maximum magnetization ratio, M_r/M_{\max} , and coercivity, H_C , behavior of SmCo/FeCo/SmCo films samples annealed at $T = 923$ K for 60 minutes and $T = 973$ K for 30 minutes. The measurement temperature was in the range between 300 and 50 K. For soft layer thickness of 10 nm the M_{\max} and M_r shows a little increment upon cooling besides H_C increase by more than 400% when temperature is lowered to 50 K. This behavior can be attributed to the exchange coupling present because the hard layer. Besides, for soft layer thickness of 25 nm, M_{\max} and M_r shows a similar behavior but for lower temperature, 50 K, a significant decoupling between both phases, soft and hard, can be expected because the “knee” appearing in the second and four quadrant close to zero applied field. This behavior is attributed to the dipolar interaction present because the soft layer thickness.

δM curves were calculated to determine the behavior of thin films system when the soft layer thickness changes. Below we describe, how these curves have the potential to yield information about the magnetic interactions in two-phase magnetic nanocomposites.

δM plots are defined starting from the observation that an assembly of uniaxial magnetically-noninteraction single-domain particles obeys the relationship:

$$M_d(H_m) = M_r - 2M_r(H_m) \quad (1)$$

where $M_r(H_m)$ is acquired after the application and subsequent removal of a directly applied field H_{\max} , and $M_d(H_m)$ is the direct current demagnetization remanence measured after applying the maximum positive magnetic field H_{\max} (starting from the demagnetized state), and then applying and removing a negative magnetic field— H_m on the demagnetization curve M_r is the maximum remanent magnetization measured after applying the maximum magnetic field [26]. If magnetic interactions are present, the deviation of $M_d(H_m)$ from $M_r - 2M_r(H_m)$ normalized to the maximum remanence:

$$\delta M \equiv \{M_d(H_m) - [M_r - 2M_r(H_m)]\} / M_r \quad (2)$$

Is a measure such interactions, and in particular, can be used to study the interplay between the exchange and the dipolar interactions in nanocomposite magnets [25]. Positive δM values are interpreted as magnetizing short-range exchange interactions, whereas negative δM values correspond to dipolar interaction [25]. Three temperatures were chosen to calculate curves, in the lower temperature the observed effect of decoupling was more significant. In **Figure 4**, δM plots show the effect of soft layer thickness as measurement temperature is decreasing. δM curve at 300 and 150 K, for sample with FeCo layer with 10 nm thickness presents a positive peak around 2 and 5 kOe, a positive peak indicates an exchange interaction coupling; for δM curve at 50 K, is

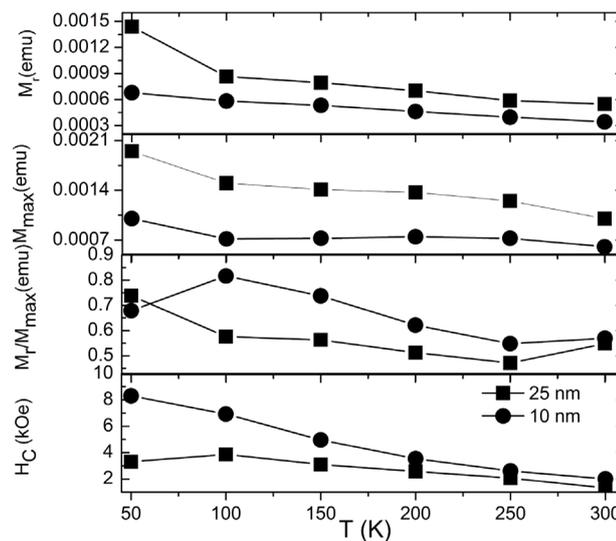


Figure 3. Magnetic properties behavior of SmCo/FeCo/SmCo films with different soft phase thickness 10 and 25 nm.

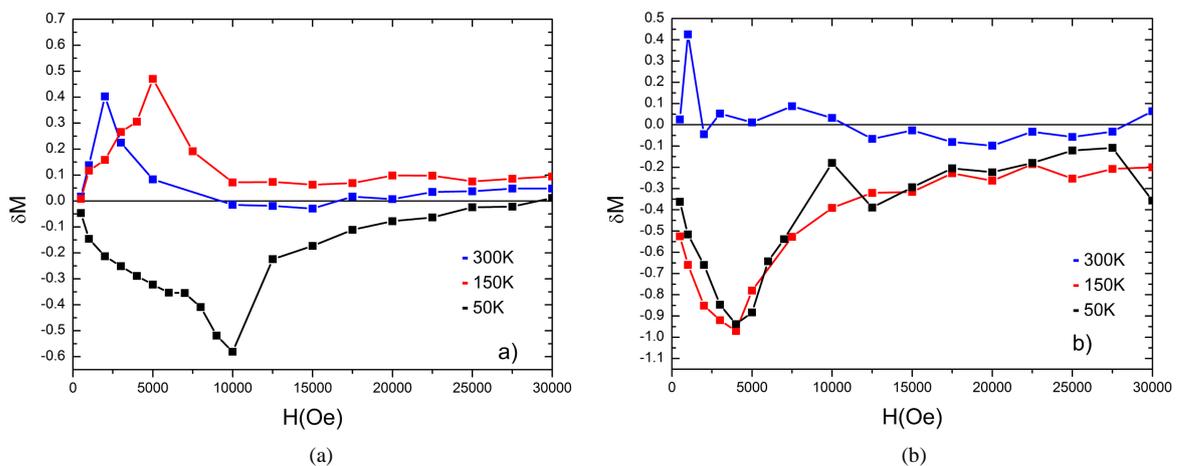


Figure 4. δM curves of SmCo/FeCo/SmCo films with different thickness (a) 10 nm and (b) 25 nm for FeCo phase.

observed a peak in the negative side, this mean a dipolar interaction is occurring but exchange coupling is stronger than dipolar interaction. Meanwhile, δM curve at 300 K, for sample FeCo layer with 25 nm thickness, present a peak in the positive side, on the other hand δM curve at 150 and 50 K, present a peak in the negative side, this mean the dipolar interaction is stronger than exchange interaction, that means SmCo/FeCo/SmCo are decouple when soft thickness layer increase and T decrease.

4. Conclusion

The magnetic properties were affected when the thickness of soft phase varies. The SmCo/FeCo/SmCo were deposited for two thickness, 10 and 25 nm, and annealed at different temperature. It was found that characteristic “knee” observed in the second quadrant demagnetizing curve is exposing the exchange decoupling between interlayers. The exchange decoupling occurs when soft thickness layer is increasing. Our study clarified how the exchange interactions decrease at low temperature as was expected because of the magnetocrystalline anisotropy dependence on it.

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