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Effect of Annealing on the Structural, Magnetic, Surface Energy and Optical Properties of $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ Films Deposited by Direct-Current Magnetron Sputtering

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Abstract: In this study, a 10–50 nm $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ alloy thin film sputtered on glass substrates was annealed at different temperatures for 1 h including room temperature (RT), 300, 350, and 400 °C. The structure, magnetic properties, surface energy, and optical properties of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ alloy were studied. X-ray diffraction (XRD) patterns of the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films showed the amorphous structure. The apparent body-centered cubic (BCC) CoFe (110) structure was exhibited after 300 °C annealing for 1 h. The 300 °C annealed $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film showed the highest CoFe (110) peak compared with other temperatures. Furthermore, the thicker the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film, the higher the CoFe (110) peak. The CoFe (110) peak revealed magneto-crystalline anisotropy, which was related to the strong low-frequency alternative-current magnetic susceptibility (χ_{ac}) and induced an increasing trend of saturation magnetization (M_s) as the thickness (t_f) increased. Due to the thermal disturbance, the χ_{ac} and M_s for the 350 and 400 °C annealed $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film decreased. The contact angles of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films were less than 90°. For all temperatures, the surface energy increased when the film thickness increased from 10 to 50 nm. In addition, the surface energies for annealed samples were comparatively higher than the as-deposited samples. The higher surface energy of 28 mJ/mm² was obtained for the 50 nm $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film annealed at 300 °C. The transmittance percentage (%) of the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ film was higher than other annealed conditions. This result contributed to the fact that higher crystallization, due to perfect band structures, may inhibit the transmission of photon signals through the film, resulting in low transmittance and high absorption.

Keywords: annealed $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films; low-frequency alternating current magnetic susceptibility (χ_{ac}); optimal resonance frequency (f_{res}); surface energy; transmittance

1. Introduction

Recently, the density of magnetic recording has been greatly improved. CoFe films are widely used in magnetoresistance random access memory (MRAM) and magnetic head applications due to their high spin polarization, high saturation magnetization (M_s), and low coercivity (H_C) [1–4]. CoFe films are free or pinned layers in spin-valued magnetic tunnel junction (MTJ) [5–10]. MTJ has a three-layer structure including the top ferromagnetic (FM1) layer, insulated tunnel barrier layer (spacer layer), and bottom ferromagnetic (FM2) layer. Researchers have made efforts to add a third element into the CoFe material in magnetic fields [11–15]. Of late, the addition of a third new element to the original CoFe material has attracted extensive attention. The addition of tungsten (W) into CoFe materials to form the CoFeW alloy has rarely been studied. Few studies have added W into CoFe. In 2012, Pai et al. studied the phase transition thickness of the rare earth transition metal W, and the effect of the MTJ spin Hall angle was studied with W as the seed layer [16]. In 2016, Ghaferi et al. used a citric acid salted bath to test the CoFeW alloy, and observed variations in W content and pH value of different concentrations. The composition ratio of CoFeW alloy in citric acid borate solution, the surface morphology, structure, and magnetic properties of the films were analyzed [17]. The addition of W in the alloy has the following advantages. As a spacer or buffer layer, W can increase the benefits of the materials including durability and strong perpendicular magnetic anisotropy (PMA) at a high temperature [18–20]. However, the disadvantages of CoFe thin films include brittleness and reduced magnetic characteristics at high temperatures. The mechanical strength and magnetic characteristics of CoFe films can be improved by adding W, because W is a hard metal with a high melting point. The addition of W as the third element may improve the mechanical properties of the CoFe alloy [21]. CoFeW is a newly emerging and a significant soft magnetic material, which can be widely used in MRAM and gauge sensors. It can also be used as a free layer or pinning layer to combine with the magnetic process, and can be compatible with other layers in a double and multi-layer system. The performance is more sensitive to RT and high temperature at which it is operated. Therefore, the effectiveness of CoFeW films in the as-deposited and annealed states is worth studying. However, at as-deposited and annealed conditions, there are few studies on the magnetic, surface energy, and optical properties of CoFeW films. Therefore, it is valuable to study the efficiency of CoFeW films deposited by magnetron sputtering at room temperature and annealed temperature. This study also focused on the CoFeW thicknesses of various as-deposited and annealed treatments to investigate the influence of crystallinity with its magnetic properties, surface energy, and optical performance. In our previous research, the CoFeV and CoFeBV alloys were investigated for their specific properties, which is arranged in Table 1 [22–26]. Table 1 suggests that CoFeV and CoFeBV thin films were investigated at the as-deposited condition. As-deposited and annealed CoFeW thin films were studied in this work. Moreover, it also indicates that the low-frequency alternate-current magnetic susceptibility (χ_{ac}) values of CoFeW thin films are larger than other CoFeV and CoFeBV thin films.

Table 1. Specific properties for various CoFeV, CoFeVB, and CoFeW materials.

Material	Thickness (nm)	Maximum χ_{ac} (a.u.)	Optimal Resonance Frequency, f_{res} (Hz)	Surface Energy (mJ/mm ²)
Glass/Co ₆₀ Fe ₂₀ V ₂₀ [22]	3–13 at RT	–	–	22.3–33.3
Glass/Co ₄₀ Fe ₄₀ V ₂₀ [23,24]	10–100 at RT	0.021–0.046	50–1000	27.8–45.4
Glass/Co ₄₀ Fe ₄₀ V ₁₀ B ₁₀ [25]	10–40 at RT	0.068–0.098	50–1000	65.5–38
Si(100)/Co ₄₀ Fe ₄₀ V ₁₀ B ₁₀ [26]	10–40 at RT	0.013–0.019	50–200	34.2–51.5
Glass/Co ₃₂ Fe ₃₀ W ₃₈ (*)	10–50 at RT and annealed conditions	0.02–0.52	50–1000	22.3–28.4

(*): current research.

2. Materials and Methods

CoFeW with a thickness of 10–50 nm was sputtered on the glass substrate at room temperature (RT) by the magnetron sputtering direct current (DC) method of 50 W power and under the following four conditions: (a) the deposited films were kept at RT; (b) annealed at a treatment temperature (T_A) at 300 °C for 1 h; (c) annealed at 350 °C for 1 h; and (d) annealed at 400 °C for 1 h. The power density was 1.65 W/cm² and the deposition rate was 1.2 nm/min. The chamber base pressure was 1.95×10^{-9} Pa, and the Ar working pressure was 2.25×10^{-5} Pa. The pressure in the ex situ annealed condition was 1.87×10^{-5} Pa with a specific Ar gas. The thick of alloy target was 2 mm. The alloy target for the composition of CoFeW was 32 at% Co, 30 at% Fe, and 38 at% W with an energy dispersive spectrometer (EDS, Hitachi, Tokyo, Japan) for spectroscopy. To determine the accurate thickness, high-resolution cross-sectional field emission scanning electron microscopy (FESEM, SU 8200, Hitachi, Tokyo, Japan) was used to study the calibration thickness of the corresponding sputtering time. The elemental composition of the films was determined by FESEM with EDS for spectroscopy. The structure of CoFeW thin films was determined by using grazing incidence X-ray diffraction (GIXRD) patterns obtained with the CuK α_1 (PAN analytical X'pert PRO MRD, Malvern Panalytical Ltd, Cambridge, UK) and a low angle diffraction incidence with about a two-degree angle. Surface roughness and morphology of the CoFeW films were studied by atomic force microscopy (AFM, NT-MDT, Moscow, Russia). The in-plane low-frequency alternate-current magnetic susceptibility (χ_{ac}) and hysteresis loop of Co₃₂Fe₃₀W₃₈ were studied by an χ_{ac} analyzer (XacQuan, MagQu Co., Ltd. New Taipei City, Taiwan) and alternating gradient magnetometer (AGM, PMC, OH, USA). First, the standard sample was calibrated by the χ_{ac} analyzer with external magnetic field. Then, the sample was inserted into the χ_{ac} analyzer. The driving frequency was between 10 and 25,000 Hz. χ_{ac} was measured by magnetization. All test samples had the same shape and size to eliminate demagnetization. The χ_{ac} value is an arbitrary unit (a.u.) because the alternating current result corresponds to the reference standard sample and is a comparative value. The relationship between magnetic susceptibility and frequency was measured by means of the χ_{ac} analyzer. The optimal resonance frequency (f_{res}) is measured by the χ_{ac} analyzer, which represents the frequency of the maximum χ_{ac} . Before measurement, the contact angle should be properly air cleaned on the surface. The contact angles of CoFeW film were measured with deionized (DI) water and glycerol. The contact angles were measured when the samples were taken out from the chamber. The surface energy was obtained from the contact angle and some calculations [27–29]. The transmittance of CoFeW was measured by a spectral intelligent analyzer. The wavelength of visible light was from 500 to 800 nm.

3. Results

3.1. Structure Property and Composition Analysis

Figure 1a–d shows the grazing incidence X-ray diffraction (GIXRD) of the as-deposited and annealed Co₃₂Fe₃₀W₃₈ thin films. No apparent crystalline peaks were obvious in Figure 1a, indicating that the as-deposited samples were amorphous structures. Therefore, it can be reasonably inferred that the thickness of the Co₃₂Fe₃₀W₃₈ thin films had a discontinuous growth model and random atomic arrangement, which led to the amorphous state [24]. Through the 300 °C annealing process, the thin film gained enough thermal energy as a driving force to transform the structure from an amorphous state to a crystalline state. The characteristic peak located at $2\theta = 44.7^\circ$ belongs to the body-centered cubic (BCC) CoFe (110), as displayed in Figure 1b. The intensity of CoFe (110) was enhanced as the thickness of the Co₃₂Fe₃₀W₃₈ thin films increased from 10 to 50 nm. The diffraction intensity in Figure 1c,d showed weaker crystalline phenomena than that in Figure 1b. The diffraction intensity of 300 °C annealed Co₃₂Fe₃₀W₃₈ thin films was higher than the as-deposited ones. After 300 °C annealing, the structure of the Co₃₂Fe₃₀W₃₈ thin films was improved from an amorphous state to a crystalline state. Figure 1e is the GIXRD pattern of the glass substrate, which also indicates an amorphous state.

Figure 1. GIXRD patterns of Co₃₂Fe₃₀W₃₈ thin films. (a) RT, (b) annealed at 300 °C, (c) annealed at 350 °C, (d) annealed at 400 °C. (e) The GIXRD pattern of the glass substrate.

Figure 2 shows the full width of half maximum (FWHM, B) of the CoFe (110) peak obtained after 300 °C annealing. According to the XRS results in Figure 1b, the B of the CoFe (110) peak decreased when the thickness of Co₃₂Fe₃₀W₃₈ thin films increased from 10 to 50 nm. Therefore, the thinner Co₃₂Fe₃₀W₃₈ thin film possessed larger FWHM. The thicker Co₃₂Fe₃₀W₃₈ thin films with annealing treatment had a smaller B.

High-resolution cross-sectional field emission scanning electron microscopy (SEM) images of the as-deposited and 300 °C annealed samples are displayed in Figure 3a,b. From the SEM results, the annealed Co₃₂Fe₃₀W₃₈ thin films became denser than the as-deposited ones. The thickness of the annealed Co₃₂Fe₃₀W₃₈ thin film decreased slightly. In particular, the XRD results of the Co₃₂Fe₃₀W₃₈ thin films showed that the films were amorphous. Through the annealing treatment, enough thermal energy was used as the driving force to change the structure from amorphous to crystalline. High density of the Co₃₂Fe₃₀W₃₈ thin films was obtained by using an annealing treatment. The plane-view images of the as-deposited and 300 °C annealed samples are shown in Figure 3c,d. From the SEM results, the as-deposited Co₃₂Fe₃₀W₃₈ thin film displayed the loose surface morphology.

Figure 2. Full width at half maximum (FWHM, B) is a function of the annealed film at 300 °C.

Figure 3. Cross-sectional SEM images of CoFeW 50 nm. (a) RT and (b) annealed at 300 °C; SEM micrographs of CoFeW 50 nm; (c) RT and (d) annealed at 300 °C.

The composition analysis for the as-deposited and annealed $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films by using EDS spectroscopy is presented in Figure 4a–d. The ratio of Co, Fe, and W in the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films was 32% for Co, 30% for Fe, and 38% for W. After 350 and 400 °C annealing, the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films possessed the oxygen composition shown in the EDS spectroscopy, which indicates that the film may have reduced magnetic properties due to the presence of oxygen after annealing. This result suggests that the composition was not the same because the multi-directional scattering and multi angle scattering of sputtered atoms were the main reasons for various compositions [30,31]. Moreover, as the target was magnetic and the thickness was 2 mm, it could certainly perturb the magnetic field of the magnetron gun, and thus induce serious film uniformity issues in both terms of thickness and composition.

Figure 4. EDS patterns of CoFeW 50 nm. (a) RT, (b) annealed at 300 °C; (c) annealed at 350 °C; (d) annealed at 400 °C.

3.2. Surface Roughness

The root-mean-square roughness (R_q) values of all $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films were detected by AFM, as shown in Figure 5. The surface roughness of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film decreased when the thickness increased. Surface roughness of the 300 °C annealed sample was smoother than other samples due to its dense structure. With the increase in surface roughness, the domain wall pinning effect is not easy to move, resulting in the decrease in the χ_{ac} value [32].

Figure 5. Surface roughness of various CoFeW thin films.

3.3. Magnetic Properties

Figure 6a–d presents the in-plane low-frequency alternative-current magnetic susceptibility (χ_{ac}) at RT, 300, 350, and 400 °C, with thicknesses ranging from 10 to 50 nm. The low frequency measured range was from 10 to 25,000 Hz and the χ_{ac} value was the highest at low frequency. The χ_{ac} values of all samples decreased with the increase in thickness. At high frequency, the χ_{ac} of the CoFeW film drops sharply, as shown in Figure 6. When the magneto-crystalline anisotropy of the CoFe (110)

crystallization effect is maximized, χ_{ac} is maximized [33,34]. When annealed at 300 °C, the optimal frequency (f_{res}) of 50 Hz had the strongest χ_{ac} value 0.52, and the spin sensitivity was the strongest.

Figure 6. The low-frequency alternate-current magnetic susceptibility (χ_{ac}) as a function of the frequency from 10 to 25,000 Hz for samples with thicknesses from 10 to 50 nm. (a) RT, (b) annealed at 300 °C, (c) annealed at 350 °C, (d) annealed at 400 °C.

Figure 7a displays the maximum χ_{ac} of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films under four different temperatures. The results indicate that maximum value of χ_{ac} increased with the increase in thickness (t_f) from 10 to 50 nm. Moreover, the film annealed at 300 °C had the highest value of χ_{ac} . In particular, the χ_{ac} value of annealed films at 300 °C was larger than that of $T_A = 350$ and 400 °C due to the thermal disturbance, which reduced the magnetic spin coupling. At the maximum frequency, χ_{ac} had the best physical meaning. At low frequency, the oscillation of the volume dipole moment in each region is the contribution to the alternate-current (AC) dipole moment. The magnetic interaction between the domains seems to be restored. Frequency is the driving force of the system. Therefore, the peak value of low frequency susceptibility corresponds to the oscillation frequency of the magnetic dipole moment in the domain. In frequency, the peak of χ_{ac} depicts the spin exchange coupling and dipole moment [35]. Therefore, the physical significance of the low frequency magnetic susceptibility peak indicates the coupling of the magnetic exchange. Moreover, the maximum χ_{ac} of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ films was compared to the $\text{Co}_{40}\text{Fe}_{40}\text{V}_{20}$ films. The highest χ_{ac} value of the 50-nm-thick $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film was larger than the $\text{Co}_{40}\text{Fe}_{40}\text{V}_{20}$ thin film [24]. Figure 7b displays the maximum χ_{ac} corresponding to the optimal resonance frequency (f_{res}) under four specific conditions. At this frequency, the maximum χ_{ac} is measured with the strongest spin sensitivity [35,36]. The optimal resonance frequency was less than 500 Hz and can be used in low frequency applications and magnetic junctions, except for the 10 nm range deposited at 1000 Hz. The f_{res} values of all $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films were less than 1000 Hz, which indicates that the film is favorable for the application of sensors, transformers, and low-frequency magnetic recording media. Figure 7c depicts the in-plane saturation magnetization (M_s) of $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ films measured by AGM under four different conditions. The results suggest that there is a significant relationship between M_s and thickness. When the film thickness increased from 10 to 50 nm, M_s tended

to be saturated, indicating the thickness effect of M_s on the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films. Moreover, the M_s value of the film annealed at 300 °C was higher than the other conditions. The maximum M_s at 50 nm was about 1133 emu/cm^3 at annealed 300 °C. Due to the strong magneto-crystalline anisotropy, it suggests that it has high spin coupling strength and can induce large M_s . It was also found that the M_s and χ_{ac} of annealed $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films were higher than those of the films before the as-deposited films due to the magneto-crystalline anisotropy, except those annealed at $T_A = 350$ and 400 °C, because the thermal interference reduces the magnetic spin coupling. From the magnetic results of Figure 7a,c, it can be reasonably inferred that the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films exhibited stronger magneto-crystalline anisotropy and better magnetic properties at 300 °C, except for annealing at 350 and 400 °C for 1 h. Due to the magneto-crystalline anisotropy, the M_s and χ_{ac} values of the retreated $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films were higher than those of the as-deposited samples. The M_s value of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films increased to 300 °C, then decreased to 350 °C, which indicates that the thermal stability of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films was better than that in the other literature [37,38].

Figure 7. (a) The maximum alternate-current magnetic susceptibility of CoFeW thin films. (b) The optimal resonance frequency of thin films with different thicknesses. (c) Saturation magnetization (M_s) of CoFeW thin films.

3.4. Analysis of Surface Energy

Figure 8a,b illustrates the contact angles of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films with deionized (DI) water and glycerol under two different temperature treatments. Before measurement, the contact angle should be properly air cleaned on the surface. An air gun may only remove dust, but no other contamination and adsorb species. The results of all samples showed that the water droplets on the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films were nearly spherical and the contact angle was less than 90°. This result showed that the thin film had flat water droplets. An oxide layer formed on the surface of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films when the sample was exposed to an atmospheric environment, where the native oxide was in the nm-scale in thickness. The surface energy of the native oxide layers was presented on the surface of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film. Surface tension is also called surface free energy. The surface tension of an oxide layer on the surface of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film is the important factor for initial deposition of a seed layer. In this work, the surface tension was measured based on an oxide layer on the surface of the

$\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films. The surface energy was obtained from the calculation of contact angles [27–29], as shown in Figure 8c. For different temperature-treated samples, the results showed that the surface energy increased when the film thickness increased from 10 to 50 nm. The surface energy of the heat-treated sample was higher than that of the as-deposited sample. The surface energy varied from 22.5 to 28 mJ/mm^2 .

Figure 8. Contact angles of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films with deionized (DI) water and glycerol. (a) RT, (b) annealed at 300 °C, and (c) surface energy of the $\text{Co}_{40}\text{Fe}_{40}\text{W}_{20}$ thin films.

3.5. Analysis of Optical Properties

Figure 9a–d shows the optical transmission spectra of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films with different thicknesses under four specific conditions. From Figure 9a, two bumps of the entire transmittance curve at 550–680 nm were observed. Due to the nanoscale effect, the band structures would gradually be separated, resulting in the density of states changing from dense to sparse. Therefore, the highest transmittance of visible light located at 580 and 630 nm could be attributed to the sparse density of states, allowing for the passing of more light when the film becomes thinner. In addition, the optical transmission spectra can be used to judge the penetration effect of the sample for different light sources. From the transmittance spectrum, the light penetration range was from 550 to 680 nm, indicating the transmission range of yellow to orange visible light. Figure 9 shows the transmittance curve at the visible wavelength of 500 to 800 nm. With the increase in thickness from 10 to 50 nm,

the transmittance of the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film decreased from 23% to 1%. The change trends of transmittance under other annealed conditions were similar. When the thickness increased from 10 to 50 nm, the transmittance decreased from 19% to 1%. Figure 9 shows that the thin and as-deposited films induced high transmittance because thicker films after the annealing treatment had more excellent crystallization and may inhibit the transmission of photon signals through the film, resulting in low transmittance [39]. In the optical result, the main motivation was to find the best optical properties and combine magnetic properties to apply to magnetic-optical fields. According to optical performance, the optimal thickness of the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films was found to be 10 nm, which is suitable for magnetic-optical recording medium applications.

Figure 9. Transmittance (%) of $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ films. (a) At RT, (b) annealed at 300 °C, (c) annealed at 350 °C, (d) annealed at 400 °C.

4. Conclusions

XRD results showed that the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ films were amorphous structures, and after more than 300 °C annealing for 1 h, the CoFe (110) crystalline structure was revealed. When the 50 Hz f_{res} was achieved, the maximum χ_{ac} for the 300 °C annealed $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film was 0.52. For all $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films with different thicknesses, the f_{res} was less than 1000 Hz, indicating that these alloy thin films are suitable for low frequency magnetic components. The diffraction intensity for the 300 °C annealed $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films was higher than that of the as-deposited and other temperature annealed thin films. In addition, the thicker $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films had a higher diffraction intensity. From the SEM results, the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film became denser after the annealing treatment. Furthermore, the thickness was slightly decreased after annealing. The AFM result showed that the surface roughness of the 350 °C annealed samples was smoother than other samples due to the denser structure. The peak of CoFe (110) showed magneto-crystalline anisotropy, which is related to the highest χ_{ac} . When the thickness increased, the induced saturation of M_s increased. In addition, the χ_{ac} and M_s of the films annealed at 350 and 400 °C decreased due to thermal interference. Furthermore, the contact angle of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ films was less than 90°.

As the thickness increased from 10 to 50 nm, the surface energy increased. The surface energy of the as-deposited $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin film was enlarged after annealing. The transmittance decreased when the thin film became thicker. The as-deposited thin films had higher transmittance because the excellent crystallization after annealing may inhibit the transmission of photon signals through the films, resulting in lower transmittance and higher absorption. The highest transmittance of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ film was 23%. Based on the results of magnetic property and surface energy, the optimal thickness of the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ film was 50 nm after 300 °C annealing. The film is suitable for use as a free layer of MTJ and can be used in the application of magnetic recording media. The article discusses how to improve the quality of the emerging $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ material by annealing at a higher temperature. In summary, through the annealing process, the $\text{Co}_{32}\text{Fe}_{30}\text{W}_{38}$ thin films showed better surface energy and higher magnetic characteristics than the as-deposited films. However, the as-deposited thin films had better transmittance than the annealed films.

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