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FERROMAGNETIC RESONANCE STUDIES IN AMORPHOUS Co-Zr FILMS

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Abstract-Ferromagnetic resonance experiments have been used to investigate the magnetic properties of amorphous $Co_{89.5}Zr_{10.5}$ thin films deposited by DC magnetron sputtering method. In the thickness range from 350 Å to 3,200 Å, measurements were carried out in a static magnetic field perpendicular and parallel to the film plane and in a conventional 9.44 GHz spectrometer at room temperature. The ferromagnetic resonance spectra by the field perpendicular to the film plane showed standing spin wave. The spacing and the relative intensities between the various spin wave resonance peaks are analysed considering surface magnetic anisotropy. The surface magnetic anisotropy constant (K_{so}, K_{sd}) of amorphous $Co_{89.5}Zr_{10.5}$ thin films are 0.02 erg/cm^2 and 0.55 erg/cm^2 respectively regardless of the film thickness except for 3,200 Å film. In case of 3,200 Å these values are 0.46 erg/cm^2 and 0.55 erg/cm^2 respectively.

I .INTRODUCTION

Recently, the concern about magnetic thin films has been focused on the increase of magnetic moment per atom due to surface effect of ultra thin film or new magnetic properties caused by the interface effect between layers of multilayered films[1, 2]. These studies on surface or interface property of magnetic thin films have been performed by SQUID[3], Brillouin Light Scattering (BLS)[4] and FMR[5] etc.

The surface studies by SQUID could be performed through a simple analysis but a variety of samples must be prepared and the difference between the properties of both sides of the thin film can not be distinguished. Also, BLS method, although it gives the information of the properties in microscopic range, must use the samples showing a strong magneto-optic interaction and low temperature experiments are not allowed.

In case of FMR experiments, though it clarifies the difference of both sides of magnetic films, the samples are limited in their shape and orientation. In the FMR experiments of magnetic thin film it is considered that the spin resonance states can be divided into two cases. The first is an uinform precessional motion of spins with the same phase. The second is a resonance with oscillation period of precessional motion in spin group with different phase by the exchange interaction between neighboring spins.

The former case is FMR and the latter is spin wave resonance. The spin wave resonance requires the external perturbation energy and the returning force against the perturbation. In spin wave resonance expreiments the perturbation energy is supplied by a microwave magnetic field and the returning force is created by the exchange force between spins. Also, the spin waves are deformed due to the boundary condition of the film surfaces. Accordingly, the information of exchange stiffness constant indicating the internal properties of thin films, namely the spin flexibility and the surface magnetic anisotropy imply the difference between the magnetic properties of inner area and the magnetic properties of the surfaces.

In this study, we made soft magnetic $Co_{89.5}Zr_{10.5}$ alloy thin films with 350 ~ 3,200 Å in thickness by DC magnetron sputtering unit. For these samples, we performed FMR experiments and applied an uniaxial anisotropy model to the observed standing spin waves. Through this process, we analyzed the surface magnetic anisotropy on both sides of the films.

II.THEORY

When the DC magnetic field H perpendicular to the film plane and a small microwave magnetic field h are applied to the film, the dynamic magnetization (m) in the films and the absorption energy follow the classical electromagnetic theories and the equations of motion of magnetization. When the electromagnetic wave applied to the film the magnetic field, the electric field and the dynamic magnetization may be expressed by Maxwell equations as follows

$$\vec{\nabla} \times \vec{h}_{rf} = \frac{\varepsilon}{c}\frac{\partial \vec{e}_{rf}}{\partial t} + \frac{4\pi\sigma}{c}\vec{e}_{rf} \qquad (1)$$

$$\vec{\nabla} \times \vec{e}_{rf} = -\frac{1}{c}\frac{\partial \vec{h}_{rf}}{\partial t} - \frac{4\pi}{c}\frac{\partial \vec{m}_{rf}}{\partial t} \qquad (2)$$

Here h and e denote the magnetic field and the electric field(*see* Fig.1). Also ε and σ represent the permitivity and the conductivity of sample. In addition, the equation of motion of magnetization considering the exchange field become

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \left(\vec{H}_{eff} + \frac{2A}{M_o^2}\nabla^2\vec{M} + \frac{\alpha}{\gamma M_o}\frac{d\vec{M}}{dt} \right) \qquad (3)$$

,where A is an exchange stiffness constant, H_{eff} is the effective magnetic field in the sample. Also the second and the third terms indicate an exchange field and a Gilbert damping factor. The boundary conditions of electromagnetic wave and dynamic magnetization at the film surface deform the spin waves given by above equations (1), (2) and (3). In particular, the boundary condition of dynamic magnetization with an uniaxial anisotropy yields[6].

$$A\frac{\partial m_{x,z}}{\partial y} - K_S m_{x,z} = 0 \qquad (4)$$

Here K_s is an anisotropy energy density per unit area, namely an surface magnetic anisotropy energy constant. Hence, the magnitude of Poyinting vector S_{av} indicating of the average energy density absorbed into the film is proportional to the impedance of the film as follows

$$S_{av} \propto Re(Z_0 + Z_d) \qquad (5)$$

where Z_0 and Z_d are impedances at both sides of the film.

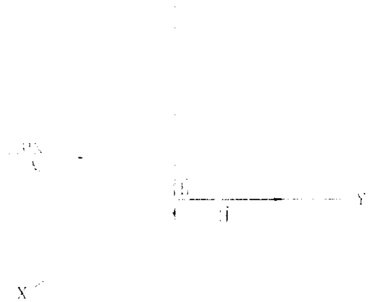

Fig.1 The coordinate system used in this calculation.

III.EXPERIMENTAL PROCEDURE

1. Sample preparation

To fabricate $Co_{89.5}Zr_{10.5}$ alloy films, we used a DC magnetron sputtering unit. The sputtering target consists of Zr flakes attached on Co target of 10 cm in diameter. The substrate was Si(100) wafer of 0.5 mm in thickness. In the sputtering chamber, the base pressure was kept $5\sim6\times10^{-7}$ Torr by a rotary pump and a turbo pump. To remove some impurities attached on the inner wall of sputtering chamber, the chamber was heated up to 100 ℃ for 1 hour and cooled down to room temperature. 350 ~ 3,200 Å thick thin films were fabricated under working gas pressure 3 mTorr.

2. FMR experiments

The prepared samples with diameter of 10 mm were cut to 3×3 mm in size and attached on quartz tube connected to goniometer. These sample were placed in the center of resonator cavity where the microwave magnetic field and the static magnetic field are orthogonal each other. Under this configuration the differential absorption curves were observed by varying the static magnetic field from 0 to 1.7 T. Where the film surface was fixed in parallel and in perpendicular with the static field. To observe the subsidiary signals the intensity of modulation signal was varied from 0.1 to 1 G. The microwave frequency and power were 9.44 GHz and 0.1 mW respectively. The modulation frequency was 100 kHz.

Ⅳ.RESULTS AND DISCUSSION

When the static field is parallel to the film surface, only one absorption curve was observed regardless of the film thickness. However, when the static field is perpendicular to the film surface, the main mode was observed in 350 Å sample and the subsidiary mode were created in 750 Å sample. In particular, the intensity of absorption energy of the main mode is large in comparision with that of the subsidiary mode regardless of the film thickness. Accordingly, if the main mode is assumed in an uniform mode, spectroscopic splitting factor g and an effective magnetization can be obtaind using an approximate resonance equation without the exchange field term.

Fig.2 shows the differential resonance absorption curve in case of 1,200 Å sample. The intensity of absorption energy according to increase of number of modes decreases gradually without oscillation.

To analyze the surface magnetic anisotropy depending on the film thickness, the exchange stiffness constant A and resistivity ρ used the values of 1.46×10^{-6} erg/cm and 13 μΩcm. Also, g−factor using the values obtained previously was applied to the equation (5). Here the magnetization M and surface magnetic anisotropy K_{so}, K_{sd} were varied. The magnetic field and the intensity of normalized absorption energy was fitted by changing the damping constant of linewidth.

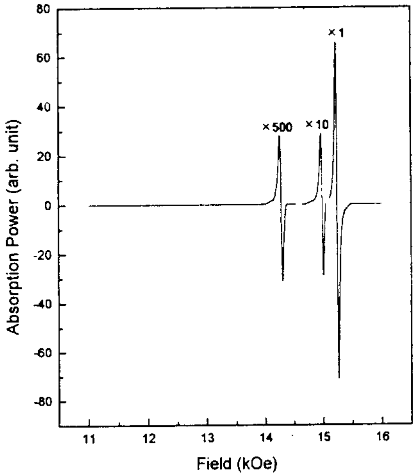

Fig.2 Spin wave derivative absorption spectrum for 1,200 Å $Co_{89.5}Zr_{10.5}$ thin film at perpendicular resonance.

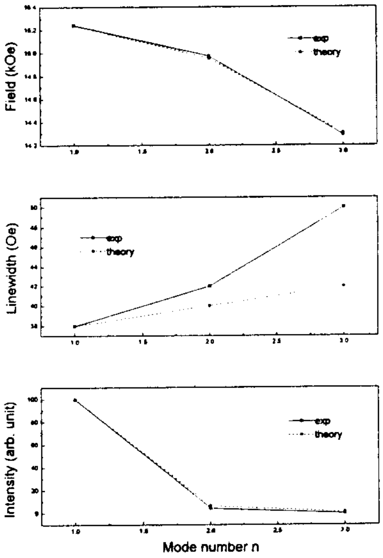

Fig.3 The mode number dependence of resonance field, linewidth and intensitu for 1,200 Å $Co_{89.5}Zr_{10.5}$ thin film.

Fig.3 shows that the resonance magnetic field, the linewidth, and the intensity of absorption power are compared to experimental data in case of K_{so} = 0.02 erg/cm^2, K_{sd} = 0.55 erg/cm^2, M = 965 emu/cc and α = 0.0102. These resonance magnetic field and the intensity of absorption power are close to experimental data but the variation of the linewidth due to the number of modes is larger than the theoretical results. Generally this phenomenon appears in the samples with the thicknesses between 750 and 2,100 Å.

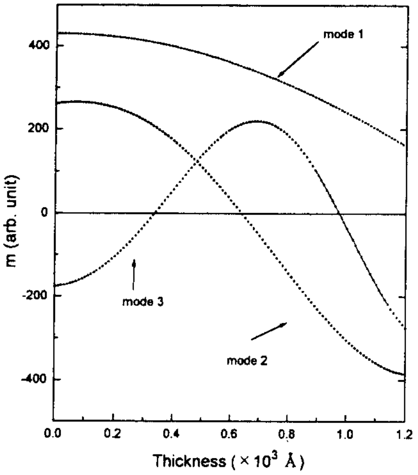

Fig.4 The shape of dynamic magnetization in 1,200 Å $Co_{89.5}Zr_{10.5}$ thin film.

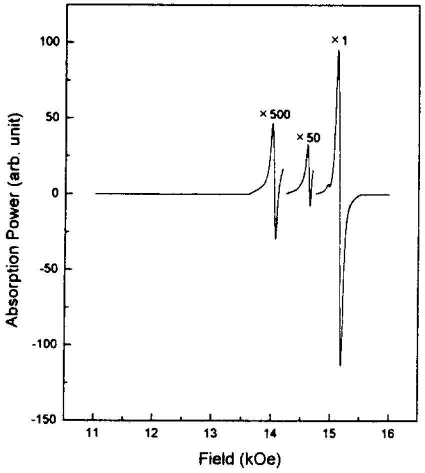

Fig.5 Spin wave derivative absorption spectrum for 3,200 Å $Co_{89.5}Zr_{10.5}$ thin film at perpendicular resonance.

Fig.4 indicates the shape of dynamic magnetization in each mode due to surface magnetc anisotropy obtained above. In case of mode 1 the amplitude of magnetization at the boundary surface due to asymmetry of surface magnetic anisotropy differs from each other but are close to that of an uniform mode. It is considered that the inhomogeneous thickness in the film is responsible for these results.

Fig.5 shows the differential absorption curves of 3,200 Å thick sample. By equation (4) the resonance magnetic field, linewidth and intensity of absorption curves for of K_{so} = 0.46 erg/cm^2, K_{sd} = 0.55 erg/cm^2, M = 962 emu/cc and α = 0.012 are compared with the experimental values in Fig.6. The linewidth observed in experiments according to the number of modes decreases with increasing of the number. The reason of this phenomenon is that the wave length of spin wave in the film become short with increase of the mode number and then the effect of electric resistivity is large in comparision with the effect of inhomogeneous thickness.

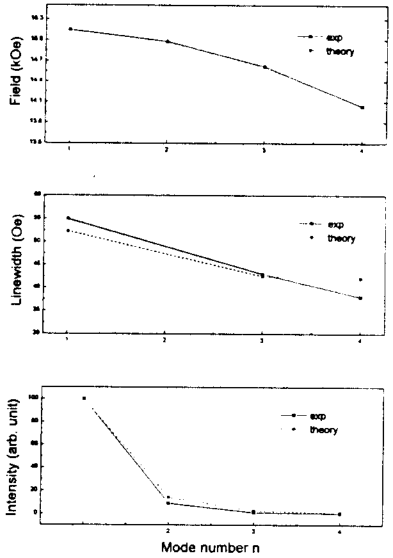

Fig.6 The mode number dependence of resonance field, linewidth and intensitu for 3,200 Å $Co_{89.5}Zr_{10.5}$ thin film.

Fig.7 shows the change of surface magnetic anisotropy according to the film thickness. When the thickness is 750~2,100 Å the surface magnetic anisotropy does not change. However, in case of 3,200 Å sample, the surface magnetic anisotropy at one side of the film increases rapidly. These results could be caused by the effect of impurities and inhomogeneous thickness in making sample or by intrinsic properties for the surface magnetic anisotropy proposed in Neel's work.

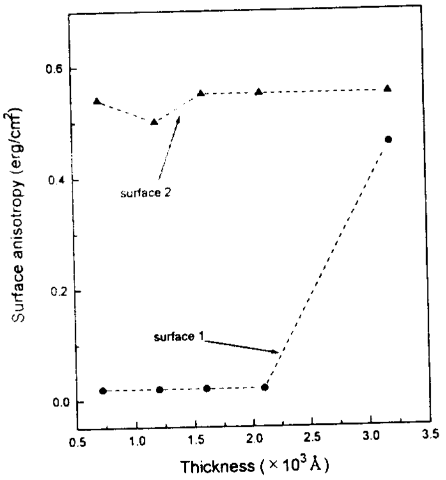

Fig.7 The thickness dependence of surface anisotropy for $Co_{89.5}Zr_{10.5}$ thin film.

V.CONCLUSION

The surface magnetic anisotropy constant K_{so} and K_{sd} of amorphous $Co_{89.5}Zr_{10.5}$ thin films are asymmetric between both surfaces. In 750 ~ 2,200 Å thick films, their magnitudes are almost constant 0.02 erg/cm^2 and 0.54 erg/cm^2. Also, the linewidth increases with increasing the number of modes, which may be caused by inhomogeneous film thickness. In case of 3,100 Å thick film K_{so} and K_{sd} are about the same, which values are 0.46 erg/cm^2 and 0.54 erg/cm^2. The linewidth decreases with increasing the number of modes. This is because the effect of electric resistivity become dominant.

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