Out-of-Plane Magnetic Anisotropy and Microwave Permeability of Magnetoelastic FeCoSiB Amorphous Thin Films

Fu-Qiang Xiao, Man-Gui Han, Hai-Peng Lu, Li Zhang, En Li, and Long-Jiang Deng

Abstract—The amorphous magnetoelastic Fe_{66}Co_{17}Si_{1}B_{6} thin films have been deposited by dc magnetron sputtering. A lot of “nano-trenches” have been observed on the film surfaces by AFM. The permeability of amorphous Fe_{66}Co_{17}Si_{1}B_{6} thin films was measured within the frequency range of 0.6 GHz–10.2 GHz. The ferromagnetic resonance frequency was found to be 1.2 GHz. MFM shows that the domain of thin film is a maze-type pattern, which indicates that an out-of-plane magnetic anisotropy exists. The out-of-plane anisotropy is believed due to the stress-induced magnetic anisotropy. It can be inferred that the internal stress is tensile stress and normal to the film plane.

Index Terms—Amorphous thin film, magnetoelastic effect, microwave permeability.

1. Introduction

It is widely accepted that soft magnetic thin films can be found applications in high frequency areas, such as magnetic recording heads, thin film inductors [1], electromagnetic noise suppressors [2], thin film stress sensors [3],[4], electromagnetic wave absorbers, etc. For bulk magnetic materials, according to the well-known Snoek’s law, the static magnetic permeability $\mu_s$ and the resonance frequency $f_r$ satisfy the following equation [5]:

$$ (\mu_s - 1) f_r = \frac{2}{3} \gamma' 4\pi M_s $$

(1)

where $\gamma' = \gamma/(2\pi)$, and $\gamma'$ is approximately equal to 3 MHz/Oe for ferromagnets. $\gamma$ is the gyromagnetic factor. $M_s$ is the saturation magnetization. The term on the right of equation is generally called “Snoek’ Constant” $S$. For most of ferrites, $S$ value is within the range of 2 GHz to 5 GHz, while for bulk ferromagnetic materials, for example Fe, $S = 40$ GHz due to its higher $M_s$ than that of ferrites [5]. For bulk materials, $S$ is only a function of $M_s$, and $M_s$ is only a function of composition of the material under studied. On the other hand, for magnetic thin films, the correlation between the $\mu_s$ and the $f_r$ is given as follows [5]:

$$ (\mu_s - 1) f_r^2 = (\gamma' 4\pi M_s)^2. $$

(2)

The above equation is called “Acher’s law”. If the resonance frequency $f_r$ is selected for some specific application. Clearly, magnetic thin films have much larger high frequency permeability than that of bulk magnetic materials. This is why researches on microwave magnetic thin films are blooming in recent years. However, it should be born in minds that the Archer’s law for thin films bases on the assumption that the film has an in-plane anisotropy. For a thin film with out-of-plane anisotropy, the Archer’s law will have a more complicate format [6],[7]. Besides, it is widely accepted that the ferromagnetic resonance frequency $f_{FMR}$ depends on

$$ f_{FMR} = f_{FMR0} \gamma' \sqrt{(H_s + H_{dc} + H_{shape} + H_{\sigma} + H_R)M_s}. $$

(3)

But according to the recent research by Craus et al., the surface roughness of thin film has a great influence on its microwave magnetic spectrum by introducing some demagnetizing factors [8]. In this case, we think (3) should be modified to incorporate the effect of surface roughness on the $f_{FMR}$. Let’s assume an equivalent magnetic anisotropy field $H_R$ which can account for the effect of surface roughness, then

$$ f_{FMR} = \mu_0 \gamma' \sqrt{(H_s + H_{dc} + H_{shape} + H_{\sigma} + H_R)M_s}. $$

(4)

Under a circumstance without external magnetic field and the magnetic thin film is amorphous, the above equation will have the following simplified format:

$$ f_{FMR} = \mu_0 \gamma' \sqrt{(H_{shape} + H_{\sigma} + H_R)M_s}. $$

(5)

It is very difficult to separate $H_{shape}$, $H_{\sigma}$ and $H_R$, and it is also difficult to study their effects on the $f_{FMR}$ value alone, but it is necessary to study the surface roughness of thin film when discussing the microwave permeability of thin film.

In this paper, the amorphous FeCoSiB thin films with...
stress-induced magnetic anisotropy have been prepared. The surface roughness of thin films and the correlation among internal stress state, magnetic domain patterns, and the microwave permeability will be discussed.

2. Experimental Details

The amorphous Fe$_{66}$Co$_{17}$Si$_{1}$B$_{6}$ thin films were prepared by the dc magnetron sputtering method. The thin films were deposited on some well-cleaned glass substrates (20 mm×20mm×0.15mm). The target size is φ, 100 mm×3 mm. The base pressure is 5×10$^{-4}$ Pa. The sputtering pressure (Ar) is 0.3 Pa. The distance between the substrate and the target is 95 mm. The sputtering power is 100 W. The thickness of thin films was measured by an atomic force microscopy (AFM) to be 400 nm. The surface topography of thin film and magnetic domain configuration were characterized on SPA-300HV scanning probe microscopy. The microwave permeability was measured based on the strip resonance cavity perturbation method with a vector networks analyzer (Agilent-E8363A). The measurement setup is shown in Fig. 1. The frequency range was 0.6 GHz–10.2 GHz. The amorphous structure of as-prepared thin films was checked by XRD (Bede D1) using Cu K$_\alpha$ radiation, the 2$\theta$ scanning range was 20°–65°. The scanning step size was 0.03°.

![Fig. 1. Instrument for measuring microwave permeability of thin film.](image)

3. Results and Discussions

Fig. 2 shows the XRD pattern of the as-prepared Fe$_{66}$Co$_{17}$Si$_{1}$B$_{6}$ thin films. It is clear that no diffraction peaks have been found in Fig. 2, which indicates that the as-deposited thin films are amorphous. The films for microwave permeability measurement, surface morphology characterization, and magnetic domain pattern characterization have not been heat-treated. As pointed out previously, the surface roughness of thin film has a significant effect on the microwave permeability by introducing some demagnetization factors$^{[10,11]}$, therefore investigation on the surface roughness will help us to identify which anisotropy are playing critical contribution to the resonance frequency.

![Fig. 2. XRD pattern of amorphous Fe$_{66}$Co$_{17}$Si$_{1}$B$_{6}$ magnetic thin film.](image)

![Fig. 3. AFM Surface topography of Fe$_{66}$Co$_{17}$Si$_{1}$B$_{6}$ amorphous thin film: (a) Planar image, (b) 3D image, (c) the surface condition of diagonal region.](image)
Fig. 3(a) shows that the particle size on thin film’s surface is not very uniform. The average particle size is about 83 nm. Fig. 3(b) shows the 3D image of surface topography. It is clear that there are many hillocks found on the film’s surface. The root mean square (rms) of surface is 4.24 nm. In order to more clearly characterize surface roughness, the surface condition of diagonal region, indicated by the black line in Fig. 3(a), is shown in Fig. 3(c). It is obvious that there are many “nano trenches”, the average height of nano trenches is less than 20 nm. According to [8], for a surface with an rms value of 4.24 nm, the demagnetization factor should be on the order of $10^{-3}$. The shape anisotropy induced by such a small demagnetization factor can be negligible.

The magnetic domains of amorphous Fe$_{66}$Co$_{17}$Si$_1$B$_6$ thin film have been characterized, as shown in Fig. 4. It is a typical “maze” type domain configuration. The average width of domains in this maze pattern is approximately 300 nm. For such a domain pattern, it can be inferred that the as-prepared amorphous Fe$_{66}$Co$_{17}$Si$_1$B$_6$ thin film has a strong magnetic anisotropy which is perpendicular to the film plane, i.e. the easy axis of magnetization is normal to the film plane [9]. In such case, the demagnetization energy will be large in this direction. In order to minimize the demagnetization energy, the domains with magnetization vectors perpendicular to the film plane ($\uparrow \downarrow$) are formed and then the “maze” type domain pattern is obtained. For amorphous magnetic thin films, there is no magnetocrystalline anisotropy, and if there is no other anisotropy present, then magnetization should be aligned on the film plane to minimize the demagnetization energy, no color contrast would be observed in the MFM image. Therefore, the stress-induced anisotropy is the cause for such a perpendicular anisotropy inferred from the “maze” type magnetic domain configuration.

Fig. 4. Magnetic domain configuration of Fe$_{66}$Co$_{17}$Si$_1$B$_6$ amorphous thin film.

Fig. 5 shows the real and imaginary parts of microwave permeability ($\mu'$ and $\mu''$) as function of frequency ($f$). At $f = 0.5$ GHz, $\mu'$ is about 120. Since the $\mu'$ values are less than 0 at higher frequency range, i.e. 2.4 GHz–10.2 GHz, we can tell that the permeability spectrum is a Lorentzian dispersion type. The ferromagnetic resonance frequency is found as 1.2 GHz. It has been reported that the Ar-sputtering pressure can greatly influence the internal stress state for the as-prepared thin films [9]. Hence, we believe that the internal stress responsible for the stress-induced anisotropy here is the consequence of sputtering process. In addition, for FeCoSiB thin film, the magnetostrictive constant $\lambda_s$ is positive [10]. For instance, the Fe$_{66}$Co$_{18}$B$_{15}$Si$_1$ amorphous magnetic material, $\lambda_s$ is $35 \times 10^{-6}$. It is well known that the direction of $M_s$ under no external magnetic field applied is determined by the sign of the product of $(\lambda_s \sigma)$. For $(\lambda_s \sigma) > 0$, $M_s$ is aligned along the direction of stress. From the observed magnetic domain pattern, the easy axis of $M_s$ is normal to the film plane. Therefore, it can be inferred that the tensile ($\sigma > 0$) is also normal to the film plane. According to [7], internal tensile stress in thin film can be completely possibly induced in an Ar-sputtering process.

4. Conclusions

In this paper, the microwave permeability of amorphous Fe$_{66}$Co$_{17}$Si$_1$B$_6$ thin films has been measured within a wide frequency range (0.6 GHz–10.2 GHz). The $f_{FMR}$ was found to be 1.2 GHz. The “maze” magnetic domain pattern indicates that there exists an out-of-plane magnetic anisotropy, which is believed due to the magnetoelastic effect. It is inferred that the internal stress in our as-prepared amorphous thin film is tensile stress and normal to the film plane, which is the consequence of sputtering process.

References

Fu-Qiang Xiao was born in Sichuan Province, China, in 1976. He received the B.Sc. degree from Chongqing University, Chongqing, in 2000. He is currently a graduate student with the School of Microelectronics and Solid-State Electronics, University of Electronic Science and Technology of China. His research interests include microwave magnetic materials (bulk materials and thin films) and giant magnetostrictive materials.

Man-Gui Han was born in Guangxi Province, China, in 1974. He received his Ph.D. degree from Iowa State University, USA, in 2004. He is currently an associate professor with the State Key Laboratory of Electronic Thin Films & Integrated Devices, University of Electronic Science and Technology of China. His main research areas include: magnetocaloric materials, magnetic refrigeration, giant magnetostrictive materials, nanotubes and nanomagnetism, microwave magnetic materials (bulk materials and thin films), magnetic microwires. He has been invited as a reviewer for Journal of Applied Physics and Journal of Materials Science. IEEE Member. He has published papers in Applied Physics Letters, Journal Applied Physics, Chinese Physics, IEEE Transactions on Magnetics and Journal of Materials Science.

Hai-Peng Lu was born in Jiangsu Province, China, in 1979. He is currently a teaching assistant with the State Key Laboratory of Electronic Thin Films & Integrated Devices, University of Electronic Science and Technology of China. His research interests include magnetic thin films for high frequency applications.

Li Zhang was born in Sichuan Province, China, in 1980. She is currently pursuing her doctoral degree with the School of Microelectronics and Solid-State Electronics, University of Electronic Science and Technology of China. His research interests include magnetic thin films for high frequency applications.

En Li was born in Sichuan Province, China, in 1970. He is an associate professor with the School of Electronic Engineering, University of Electronic Science and Technology of China. His main research area is microwave measurements.

Long-Jiang Deng was born in Sichuan Province, China, in 1966. He is currently a professor with the State Key Laboratory of Electronic Thin Films & Integrated Devices, University of Electronic Science and Technology of China. His research interests include electromagnetic wave absorbing materials.