Transactions of the Materials Research Society of Japan 28 [4] 1173-1176 (2003)

Morphology and Magnetic Characteristics in Initial Growth Stage of Fe Films Deposited by Dual Ion Beam Sputtering

Satoshi IWATSUBO
Toyama Industrial Technology Center, 383 Takata, Toyama, Toyama 930-0866
Fax: 81-76-433-5466, e-mail: iwatsubo@itc.pref.toyama.jp

Fe films without Ar bombardment [B_{NON}] and with Ar bombardment of 200 eV [B_{DUR}] were deposited by dual ion beam sputtering. The film thickness t_F dependence of the morphology and magnetic characteristics was investigated in the wide range between 0.5 and 600 nm. The magnetic characteristics were measured for a specimen with an overcoated thin layer of Au to protect the oxidization of the films. The film growth process for B_{NON} and B_{DUR} was very different. For B_{NON}, the film structure changed from island to layer at t_F between 8 and 16 nm. For B_{DUR}, the surface appearance was smoother than that of B_{NON} and the films with t_F above 1 nm were in layer structure. The saturation magnetization $4\pi M_S$ of B_{NON} took the almost constant value of 21.5 kG. $4\pi M_S$ of B_{DUR} decreased from 21.5 to 16.5 kG at t_F below 8 nm owing to the mixing region between the films and the substrates by the bombardment. The coercivity H_C of B_{NON} and B_{DUR} took the maximum values at t_F of 16 and 2 nm, respectively. Their values were approximately equal to the thickness where the structure changed. H_C of B_{DUR} took the constant value of 2.5 Oe at t_F above 16 nm, since the films were completely in layer structure. It was found that Ar bombardment could decrease the thickness of island structure in the initial growth stage and enhanced the soft magnetic properties of the Fe films by the smoothing effect.
Key words: Fe, ion beam, sputtering, magnetic characteristics, thin film

1. INTRODUCTION

In film deposition, morphology of the film drastically changes at the initial growth stage. So, magnetic characteristics of ultrathin layers in multilayer for TMR and GMR elements may be different from those of the thick film. The ultrathin film is nearly in the initial growth stage. In most cases, the quality of the initial growth region is not good due to nonuniform island structure with worse crystallinity. In addition, shape of interface of layers in multilayer is also an important factor to decide the characteristics of the devices. Generally, relationship between surface energy of film and one of substrate impacts film structure in the initial growth stage. So, surface diffusion and mobility of adatoms during deposition are essential parameters for the film growth. Ar ion bombardment by dual ion beam sputtering can directly control their parameters. Actually, Ar bombardment can modify the grain shape and the roughness of film surface. So, the bombardment with the optimum energy can form very smooth surface. [1], [2] The effect may be useful to suppress the initial growth and to improve the magnetic characteristics of the ultrathin films. In this study, the two kinds of Fe films, without Ar bombardment [B_{NON}] and with Ar bombardment during deposition [B_{DUR}] were deposited by dual ion beam sputtering. The relationship between the morphology and the magnetic characteristics was investigated as a function of the film thickness t_F.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the schematic illustration of the dual ion beam sputtering apparatus in this study. Both ion sources were the Kaufman type. The residual gas pressure in the sputtered-deposition chamber was 6×10^{-5} Pa. Ar gas for sputtering and bombarding was introduced into each ion source at the gas flow rate of 2 sccm. The total pressure was 7.2 mPa. A high purity (99.9%) Fe target and water-cooled glass substrates were used. The voltage and the current for the sputtering ion source were set at 1200 V and 50 mA, respectively. The films without Ar bombardment [B_{NON}] were deposited by ion beam sputtering.

Next, the acceleration voltage V_A of the bombarding Ar ions was fixed at 200 V to deposit the films with the extremely smooth surface. [2] Then, the current density of bombarding Ar ions onto the substrate surface was fixed at value of 0.49 A/m^2. Under this condition, the number of Ar ions to bombard the substrate surface is nearly the same as that of the sputtered Fe atoms estimated on the deposition rate without Ar bombardment. The films with Ar bombardment [B_{DUR}] were deposited by dual ion beam sputtering. t_F was measured by the calibrated thickness sensor of quartz-crystal oscillator and was varied in the range between 0.5 and 600 nm. The morphology in the films was observed by an atomic force microscope (AFM). The magnetic characteristics were measured using by a vibrating sample magnetometer (VSM) for the specimen with an overcoated Au thin layer to protect oxidization of Fe films.

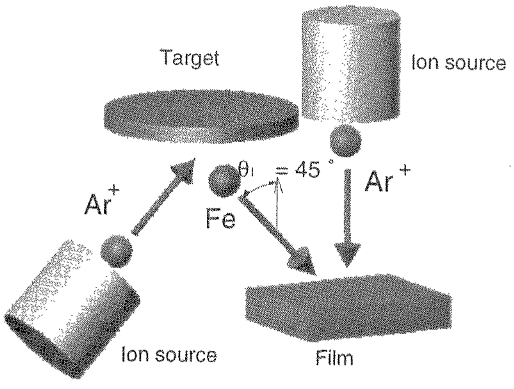
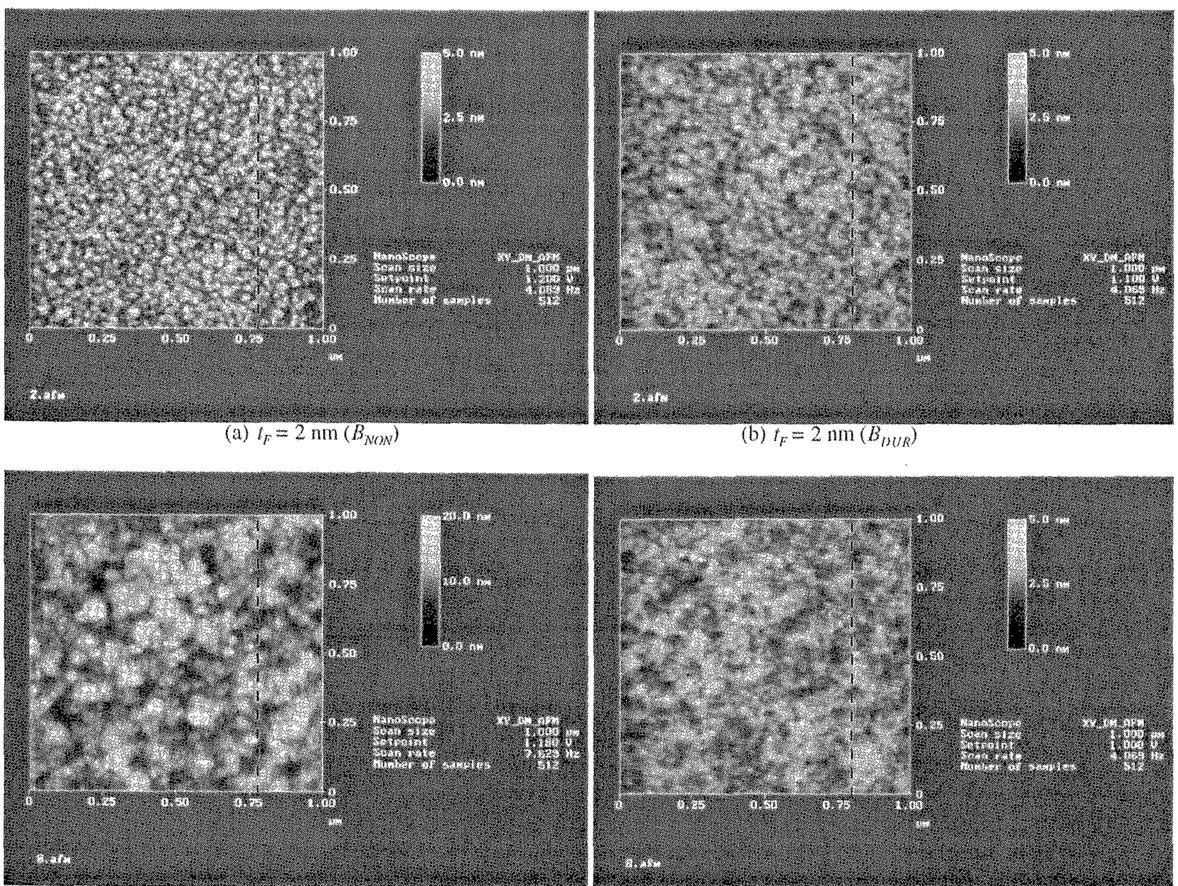


Fig. 1 Layout of the dual ion beam sputtering apparatus

3. RESULTS AND DISCUSSION

Figure 2 shows the typical AFM images Fe films with t_F of 2 and 8 nm deposited by B_{NON} and B_{DUR}. The scanning area of the images is 1x1 μm^2. The maximum scale of high for (a), (b) and (d) is 5 nm and only one for (c) is 20 nm. For B_{NON}, spherical grains were revealed. Their grains were large and combined together, as t_F increased. Their surface morphology of the films looks like island structure. On the other hand, the surface appearance of B_{DUR} was smoother than that for B_{NON}, so that the surface morphology looks like layer structure. So, in order to quantitatively analyze the film structure, the surface roughness of the films was measured in detail.

Figure 3 shows the typical roughness profiles of the films. The profiles indicate the cross sections at the parts of the broken lines in Fig. 2. The height parameter Rz indicates the average height difference between the five highest peaks and the five lowest valleys in the sampling length. Rz of the substrate was 0.4 nm. At t_F of 2 nm, Rz of B_{NON} and B_{DUR} took the values of 2.4 and 1.1 nm, respectively. Rz of B_{NON} was larger than t_F. Rz of B_{DUR} was a half of t_F. At t_F of 8 nm, Rz of B_{NON} was nearly equal to t_F and Rz of B_{DUR} was a quarter of t_F.



(a) t_F = 2 nm (B_{NON}) (b) t_F = 2 nm (B_{DUR})

(c) t_F = 8 nm (B_{NON}) (d) t_F = 8 nm (B_{DUR})

Fig. 2 AFM images of Fe films with t_F of 2 and 8 nm for B_{NON} and B_{DUR}.

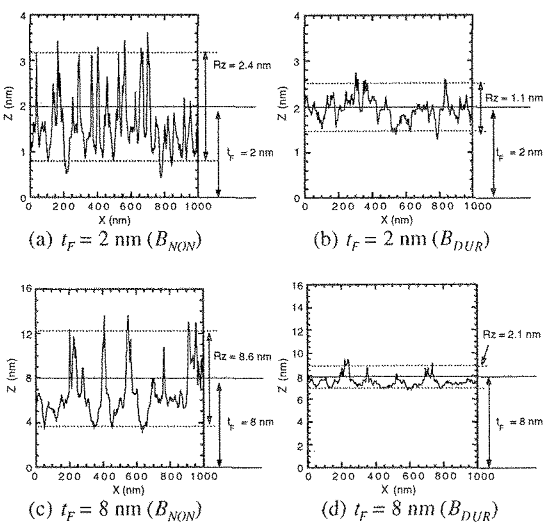


Fig. 3 Roughness profiles and height parameter Rz of films with t_F of 2 and 8 nm for B_{NON} and B_{DUR}.

To be clear the film structure, the formal parameter $R_{L/I}$ can be defined as the ratio of thickness of layer part t_L to thickness of island part t_I. Figure 4 shows the geometric relationship among t_F, Rz, t_L and t_I. t_F is based on mass measured by method of quartz crystal oscillator and Rz is the distance between the highest peak and the lowest valley of the film surface. Accordingly, t_L is t_F minus $Rz/2$ and t_I is equal to Rz, so that,

$$R_{L/I} = \frac{t_L}{t_I} = \frac{t_F}{Rz} - \frac{1}{2}. \qquad (1)$$

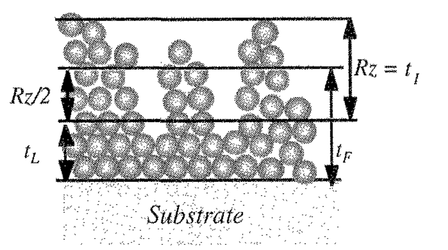


Fig. 4 Illustration of geometric relationship among t_F, Rz, t_L and t_I.

Figure 5 shows the relationship between $R_{L/I}$ and the film structure. If $R_{L/I}$ of the film is between 0 and 1, the film is in island structure with thin layer part. If $R_{L/I}$ is equal to 1, the thickness of island and layer is same and the film is in transitional structure. So, if $R_{L/I}$ is larger than 1, the film is in layer structure. As $R_{L/I}$ increases, The film approaches completely in layer structure, the typical characteristic as the film appears.

Figure 6 shows the t_F dependence of Rz and $R_{L/I}$. Rz of B_{DUR} was larger than that of B_{NON}. Both Rz of B_{NON} and B_{DUR} increased with an increase of t_F. Especially, Rz of B_{NON} abruptly increased at t_F below 8 nm.

$R_{L/I}$ of B_{NON} was nearly equal to 0.3 at t_F in the range between 0.5 and 4 nm and increased at t_F above 4 nm. So, $R_{L/I}$ was larger than 1 at t_F around 16 nm. On the other hand, $R_{L/I}$ of B_{DUR} increased from 0.8 in proportion to t_F and was larger than 1 at t_F above 1 nm. So, the film structure was in layer at t_F above 16 nm for B_{NON} and 1 nm for B_{DUR}. These results indicate that Fe films without Ar bombardment easily grow in island structure and Ar bombardment can suppress the growth.

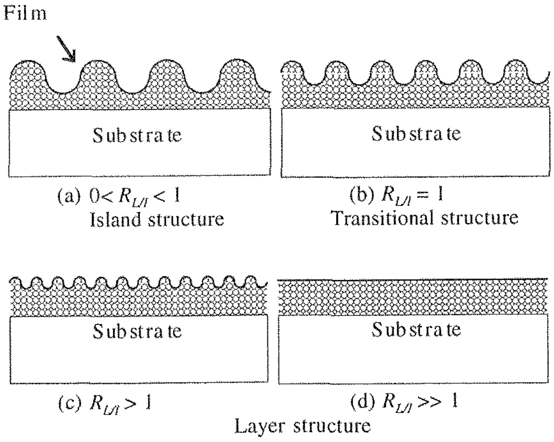


Fig. 5 Relationship between $R_{L/I}$ and film structures.

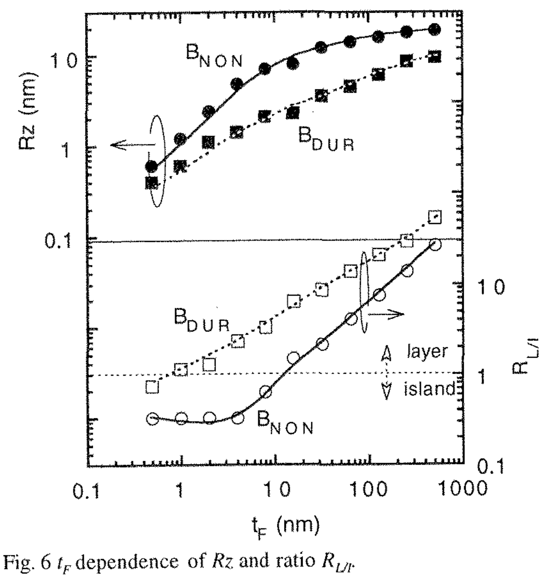


Fig. 6 t_F dependence of Rz and ratio $R_{L/I}$.

Figure 7 shows the t_F dependence of the saturation magnetization $4\pi M_S$. $4\pi M_S$ of B_{NON} was the constant value of 21.5 kG. $4\pi M_S$ of B_{DUR} decreased at t_F below 8 nm. $4\pi M_S$ took the minimum value of 16.6 kG at t_F of 0.5 nm. The region of the atomic collisions between Ar ions with 200 eV and Fe atoms of the films is estimated in the range of several nm. In the initial growth stage, the implantation of the Ar ions and the knock on the Fe atoms into the substrate by the atomic collisions can't be negligible. Therefore, the decrease of $4\pi M_S$ is mainly attributed to decrease in the net thickness of pure Fe film caused by the mixing region of Fe and O contained the glass substrates (SiO_2). So, the thickness of the mixing region without magnetization t_N was estimated from the decrease of $4\pi M_S$ and the ratio of t_N to t_F $R(t_N/t_F)$ was calculated.

Figure 8 shows the t_F dependence of $R(t_N/t_F)$. $R(t_N/t_F)$ of B_{NON} was smaller than 1 %. On the other hand, $R(t_N/t_F)$ of B_{DUR} was higher than 15 % at t_F below 1 nm. This result indicates that the mixing region without magnetization may influence the magnetic characteristics of the films.

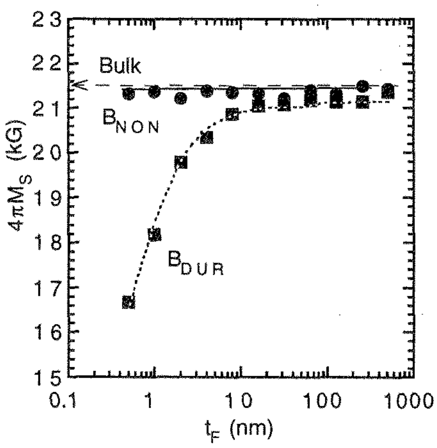


Fig. 7 t_F dependence of saturation magnetization $4\pi M_S$.

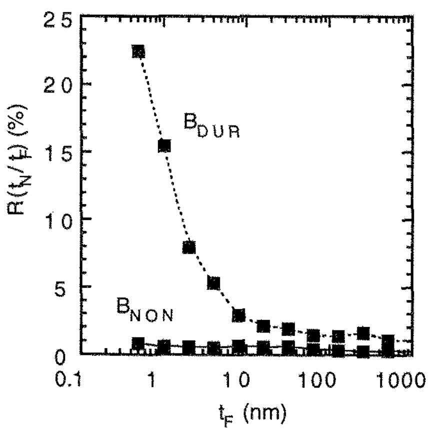


Fig. 8 t_F dependence of ratio R (t_N/t_F).

Figure 9 shows the t_F dependence of the coercivity H_C. H_C of B_{NON} and B_{DUR} took the maximum values at t_F of 16 and 2 nm, respectively. At their values of t_F, the films were in transitional structure between island and layer where $R_{L/I}$ was nearly equal to 1. There is a possibility of high correlation between H_C and $R_{L/I}$. So, the $R_{L/I}$ dependence of H_C was shown in Fig. 10. H_C took the maximum value at $R_{L/I}$ around 1 except the films of $R(t_N/t_F)$ higher than 10 %. This result indicates that the Fe films with good soft magnetic properties must be in layer structure as smooth as possible.

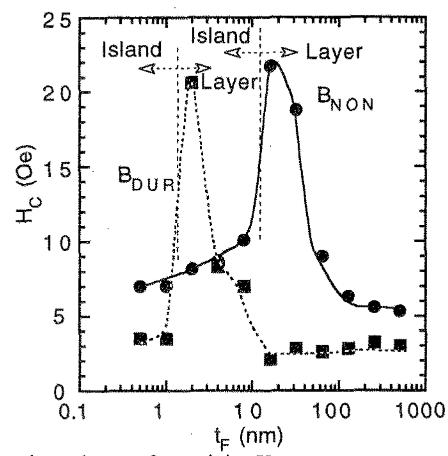


Fig. 9 t_F dependence of coercivity H_C.

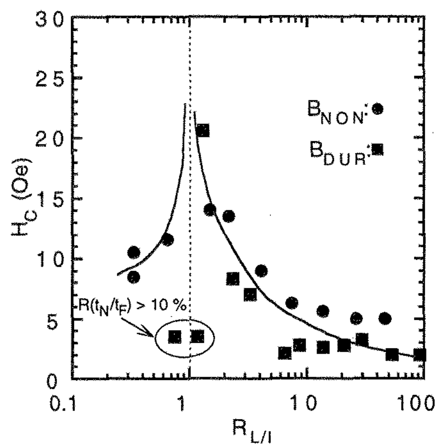


Fig. 10 $R_{L/I}$ dependence of H_C.

4. CONCLUSION

The two kinds of Fe films without and with Ar bombardment were deposited as a function of the film thickness in the wide range between 0.5 and 600 nm. The Fe films without Ar bombardment changed from island structure to layer structure at t_F between 8 and 16 nm. The films with Ar bombardment were in layer structure at t_F above 1 nm. $4\pi M_S$ of the films with Ar bombardment decreased at t_F below 8 nm owing to the implantation and the knock on Fe atoms into glass substrates. There is a high correlation between H_C and the formal parameter $R_{L/I}$. H_C took the maximum value at $R_{L/I}$ around 1 and decreased as the films approached completely in layer structure. $R_{L/I}$ of the films with Ar bombardment was much smaller than that of without Ar bombardment. It was found that Ar bombardment decreased the thickness of island structure and enhanced the soft magnetic properties of the Fe films by the smoothing effect.

References

[1] S. Iwatsubo and M. Naoe, IEEE Trans. Magn., **37**, 2298 (2001)
[2] S. Iwatsubo, T. Takahashi and M. Naoe, J. Appl. Phys., **83**, 6667 (1998)

(Received February 5, 2003; Accepted June 30, 2003)