Magnetic and electrical properties of amorphous CoFeB films

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CoFeB films were deposited on glass substrate by the sputtering method. From x-ray-diffraction and electron-diffraction-ring patterns, the major phase in the as-deposited CoFeB film is amorphous (or nanocrystalline). However, we could also identify a minor CoFe(110) crystalline phase in the film. We have tried to suppress this crystalline phase by changing the Ar partial pressure ($P_{Ar}$) during deposition and found that the optimal condition is $P_{Ar}=5 \times 10^{-3}$ Torr. Because the electrical resistivity value ($\rho$) of the film is in general larger than $100 \mu\Omega$ cm, it also indicates that the amorphous phase is dominant. From the temperature coefficient of resistance measurement, we learn that the amorphous phase in the CoFeB film crystallizes in succession at two higher temperatures ($T_{cr1}$ and $T_{cr2}$) than the room temperature (RT). Besides the electrical properties, the film thickness ($t_f$) dependence of saturation magnetization ($M_s$), saturation magnetostriiction ($\lambda_s$), and coercivity ($H_c$) has also been discussed. From the Auger-depth profile analysis, it is found that there is one CoO$_x$ (with $0.4 \leq x < 1$) oxide layer, about 15 Å in thickness, lying near the top surface of the CoFeB film, and another CoO$_x$ oxide layer, about 20 Å, lying near the CoFeB/glass interface. At RT CoO$_x$ is supposed to be paramagnetic. However, due to the proximity effect between CoO$_x$ and CoFeB, the CoO$_x$ layers may become ferromagnetic with the average magnetization $M_{ox}$. By fitting the $M_s$ data as a function of $(1/t_f)$, we can show that the last conjecture is correct, and $M_{ox}$ is not zero. The CoO$_x$ layer plays an important role on $M_s$, $\lambda_s$, and $H_c$ of the CoFeB films with $t_f$ ranging from 50 to 503 Å.

I. INTRODUCTION

The giant magnetoresistance (GMR) or tunneling magnetoresistance (TMR) property of CoFeB materials has attracted extensive attention in recent years. The amorphous CoFeB film has high spin polarization, which could lead to a high TMR value at room temperature. The giant magnetostriction property of CoFeB materials has at-tracted extensive attention in recent years. The amorphous phase in the CoFeB film crystallizes in succession at two higher temperatures ($T_{cr1}$ and $T_{cr2}$) than the room temperature (RT). Besides the electrical properties, the film thickness ($t_f$) dependence of saturation magnetization ($M_s$), saturation magnetostriiction ($\lambda_s$), and coercivity ($H_c$) has also been discussed. From the Auger-depth profile analysis, it is found that there is one CoO$_x$ (with $0.4 \leq x < 1$) oxide layer, about 15 Å in thickness, lying near the top surface of the CoFeB film, and another CoO$_x$ oxide layer, about 20 Å, lying near the CoFeB/glass interface. At RT CoO$_x$ is supposed to be paramagnetic. However, due to the proximity effect between CoO$_x$ and CoFeB, the CoO$_x$ layers may become ferromagnetic with the average magnetization $M_{ox}$. By fitting the $M_s$ data as a function of $(1/t_f)$, we can show that the last conjecture is correct, and $M_{ox}$ is not zero. The CoO$_x$ layer plays an important role on $M_s$, $\lambda_s$, and $H_c$ of the CoFeB films with $t_f$ ranging from 50 to 503 Å.

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FIG. 1. The CoFeB film was analyzed by the Auger-depth profile analysis.
steps. This provides valuable information for the CoFeB-type magnetic sensors, which must sustain under the higher working temperatures than RT.

II. EXPERIMENTS

CoFeB films with the film thickness ($t_f$) ranging from 25 to 503 Å were deposited by dc magnetron sputtering onto a glass substrate, respectively. The target compositions of CoFeB alloy are 78 at. %Co, 11 at. %Fe, and 11 at. %B. All the CoFeB films were made at RT. The typical base chamber pressure was $2 \times 10^{-7}$ Torr and the working chamber pressure was $5 \times 10^{-3}$ Torr. Cross-sectional transmission electron microscopy (XTEM) pictures of several CoFeB films were taken to calibrate the in situ Sycon thickness monitor. Then, the thickness ($t_f$) of each film sample, for later measurements, was read directly from this calibrated thickness monitor.

In order to study the top and bottom interfaces, we did the Auger-depth profile analysis on one CoFeB film sample. The structure of each film was characterized by the x-ray-diffraction method using Cu $K\alpha_1$ line. We also examined a typical CoFeB film by the plane-view TEM. The surface morphology or roughness ($S_a$) was revealed by an atomic force microscope (AFM). The in-plane magnetic hysteresis loop of each CoFeB film was measured by LakeShore model 7300 vibrating-sample magnetometer (VSM). $\lambda_s$ was measured by the optical-cantilever method. The details of this method have been described in Refs. 11 and 12. The room-temperature electrical resistivity ($\rho$) and the high-temperature resistance ($R$) were measured by the standard four-point-probe method. The temperature coefficient of resistance (TCR) value is defined by the following formula: $\text{TCR} = (1/R)(\Delta R/\Delta T)$, where $R$ is the electrical resistance at temperature $T$, and $\Delta R$ is the resistance difference due to the temperature change $\Delta T$. All the measurements mentioned above, except TCR, were done at RT.

III. RESULTS AND DISCUSSION

In order to study the CoO$_x$/CoFeB and CoFeB/glass interfaces, a CoFeB film with $t_f=100$ Å has been taken for the Auger-depth profile analysis, as shown in Fig. 1. The ion sputtering rate used in the Auger-depth measurement is assumed to be 20 Å/min, which is actually the rate for SiO$_2$. The results in Fig. 1 can be divided into four regions: (I) a CoO$_x$ layer on the top, (II) a CoFeB layer in the middle, (III) another CoO$_x$ layer near the CoFeB/glass interface, and (IV) glass substrate, respectively. In region (I), the oxygen concentration $C_O$ decreases linearly, while $C_{Co}$ increases linearly. That is, in region (I) $x$, where $x=C_O/C_{Co}$ varies roughly from 1 to 0.4 for CoO$_x$. In region (II), the concentration ratio of $C_{Co}:C_{Fe}:C_B$ is constant and roughly equals to 78:11:11. In region (III), we can also define the second CoO$_x$ layer, where $C_O$ and $C_B$ increase and then decrease, while $C_{Co}$ decreases only. Once again, the same criterion, $0.4 < x < 1$, has been used to define region (III). Hence, according to this depth profile, the thickness of the outer CoO$_x$ layer ($L_{ox}$) is about 15 Å and that of the inner CoO$_x$ layer ($L_{ox}$) about 20 Å.

The TEM plane-view graph of the as-deposited CoFeB film with $t_f=503$ Å is shown in Fig. 2(a). In this figure, we find that the lateral grain size ($D_L$) of the amorphous (or nanocrystalline) matrix in the as-deposited CoFeB is as small as 224 Å. Note that it is known that the thickness of the grain ($D_L$), as determined from the peak broadening of the x-ray-diffraction line, is usually much smaller than the corresponding $D_L$. Hence, the average grain size ($D_{avg}$) is defined as $D_{avg}=(2/3)D_L +(1/3)D_T$, of the as-deposited CoFeB film in Fig. 2(a) must be lower than 224 Å. The insert in Fig. 2(a) shows the electron diffraction pattern of the same film. From this insert, we see that there is a main and breadth pattern from the amorphous phase, and the other rings patterns, each of which is superimposed on a spot pattern from the crystalline phase. Figure 2(b) shows the TEM plane-view graph of the CoFeB film after the TCR measurement. Apparently, after the thermal cycle of the TCR measurement (up to 200 °C) $D_L$ grows larger and becomes 494 Å. Moreover, from the insert in Fig. 2(b), we discover that the number of the ring patterns has increased a great deal. Therefore, we believe that after the TCR measurement the CoFeB film has been crystallized and its lateral grain size $D_L$ may have increased 2.2 times. In addition, the crystal structure of the as-deposited CoFeB film was analyzed by x-ray diffraction. A typical result is shown in Fig. 3. Besides the high level of the
As discussed in Refs. 13–16, the gradual increase of \( /H_2O_849 /H_2O_849 \) as \( t_f /H_2O_849 \) effects. However, the sharp increase of feature \( 4 /H_2O_849 \) is seen that the thickness \( /H_2O_849 \) can summarize the following features: first, all the phenomena in general agree with the understanding of roughness-to-thickness ratio \( /H_9262/H_9024 \). These phenomena support the crystallites coexisting with the amorphous matrix. We have tried to suppress the crystalline phase by varying the Ar pressure \( P_{Ar} = 5 \times 10^{-3} \) Torr is the optimal condition for CoFeB.

The roughness-to-thickness ratio \( (S_y/t_f) /H_20849 \) is shown in Fig. 4. It is seen that the \( S_y/t_f /H_20849 \) value increases as \( t_f /H_20849 \) decreases. These phenomena in general agree with the understanding about the film-growth process, using the sputtering method.

Figure 5 shows the electrical resistivity \( (\rho) \) versus film thickness \( (t_f) /H_20849 \) plot for the CoFeB film. The results may indicate two things: first, all the \( \rho /H_20849 \) values are larger than 100 \( \mu\Omega /H_20849 \) cm, which means that the major phase in the CoFeB films is amorphous. This is consistent with the conclusion drawn from the TEM and x-ray studies. Second, \( \rho /H_20849 \) increases as \( t_f /H_20849 \) decreases. From the \( \rho \) vs \( t_f /H_20849 \) plot, as shown in Fig. 5, we can summarize the following features: (1) in the range of 50 Å \( \leq t_f \leq 503 \) Å, \( \rho /H_20849 \) increases from 133 to 664 \( \mu\Omega /H_20849 \) cm and (2) at \( t_f = 25 \) Å, \( \rho /H_20849 \) becomes very large (up to \( 5 \times 10^3 /H_20849 \) \( \mu\Omega /H_20849 \) cm).

As discussed in Refs. 13–16, the gradual increase of \( \rho /H_20849 \) of feature (1) is due to the surface oxidation or roughness effect. However, the sharp increase of \( \rho /H_20849 \) of feature (2) must be due to the fact that the film is at the precoalescence (or discontinuous) stage. The tunneling mechanism, valid for this \( t_f = 25 \) Å film, explains why \( \rho /H_20849 \) is extremely large. Figure 6 shows the TCR plot of one CoFeB film. From this plot, we learn that the crystallization of the CoFeB film occurs in two successive steps: one at the crystallization temperature \( T_{cr1} /H_20849 \) = 61 °C and the other at \( T_{cr2} = 172 \) °C. The average TCR value below \( T_{cr1} /H_20849 \) is \( 6.12 \times 10^{-4}/1 ^/H_20849 \) °C.

The magnetization \( (M_j) /H_20849 \) data of CoFeB films are displayed in Fig. 7. Note that for the CoFeB film with \( t_f = 25 \) Å, our VSM could only detect the diamagnetic signal from the glass substrate. The reason is twofold. First, the volume of this CoFeB film is much smaller than that of the substrate. Second, the magnetic signal from this CoFeB film is further weakened due to the discontinuous condition of the film. For the CoFeB films with \( t_f \geq 50 \) Å, we had no problems in obtaining their magnetic hysteresis signals and did the substrate correction for each of them. From Fig. 7, we may assume the saturation magnetization of the amorphous CoFeB bulk \( (M_s) /H_20849 \) to be 1357 G. Further, the Néel temperature \( (T_N) /H_20849 \) of bulk CoO is 293 K. Also, \( T_N /H_20849 \) of CoO film must be less than that of CoO bulk. Hence, the CoO layer in our CoFeB film is supposed to be paramagnetic at RT. However, due to the proximity effect between the CoO and CoFeB, the magnetic property of the two CoO layers may become ferromagnetic with magnetization \( M_{ox} /H_20849 \). For simplicity we assume the magnetization of the two CoO layers to be equal. From previous discussion on the results of Auger-depth analysis, our CoFeB film with thickness \( t_f /H_20849 \) is composed of

FIG. 3. X-ray measurement of glass/CoFeB 402 Å film was analyzed. The peak shows the existence of the crystalline CoFe(110) phase. \( I_0 /H_20849 \) is the background intensity from the amorphous matrix. The insert shows the relationship between the Ar partial pressure during sputtering and the relative intensity of the CoFe(110) peak.

FIG. 4. The surface roughness \( (S_y) /H_20849 \) was examined by an AFM. The roughness-to-thickness ratio \( (S_y/t_f) /H_20849 \) is a function of CoFeB film thickness \( (t_f) /H_20849 \).

FIG. 5. Electrical resistivity \( (\rho) /H_20849 \) plotted as a function of CoFeB thickness \( (t_f) /H_20849 \).

FIG. 6. The TCR electrical properties of the glass/CoFeB(503 Å), \( (T_{cr1}) /H_20849 \) and \( T_{cr2} /H_20849 \) are the crystallization temperatures.
Since to 50 Å. Finally, in zone II the multilayered structure: (I) an outer CoO$_x$ layer with thickness $t_f$ on the top, (II) a CoFeB layer with thickness $(t_f-t_{ox})$ in the middle, and (III) another inner CoO$_x$ layer with thickness $t_{ox}$ near the CoFeB/glass interface. Once again, from Fig. 1 we define $t_{ox}=\frac{1}{2}(t_f+t_{ox})=17.5$ Å. Then, according to the simple addition rule, the saturation magnetization ($M_s$) of the CoFeB film can be described as

$$M_s = M_{FeB} = M_f - 2t_{ox}M_{ox} + 2t_{ox}M_{ox}.$$  

From Eq. (1), it is easy to show that

$$M_s = M_f = 1 - (\Delta/t_f),$$

where $2t_{ox}=\Delta/[1-(M_{ox}/M_f)]$. By using Eq. (1) as the fitting equation in Fig. 7 (the dotted line), we find that $\Delta = 25$ Å. Since $t_{ox} = \Delta/2[1-(M_{ox}/M_f)]$, it is easy to obtain $M_{ox}/M_f = 0.29$ or $M_{ox} = 394$ G. This gives a proof to our previous conjecture that the magnetic state of the CoFeB layer is ferromagnetic.

The results of $\lambda_s$ data are shown in Fig. 8. $\lambda_s$ of the as-deposited CoFeB film is positive for all the $t_f$ values. In general, the $\lambda_s$ vs $t_f$ plot in Fig. 8 can be divided into three zones. In zone (A), where $0<t_f<50$ Å, the film is discontinuous. We could hardly get any $\lambda_s$ signal. In zone (B), $\lambda_s$ increases from $4 \times 10^{-6}$ to $1 \times 10^{-5}$, as $t_f$ decreases from 90 to 50 Å. Finally, in zone (C) $\lambda_s$ increases from $6.5 \times 10^{-6}$ to $1.3 \times 10^{-5}$, when $t_f$ decreases from 503 to 95 Å. The only way to analyze the $\lambda_s$ data in zone (C) is by employing the modified Néel model. In this model, in order to treat the CoO$_x$ layers as the surface effect of the CoFeB film, we must set a lower thickness limit ($t_0$) in describing $\lambda_s$. Hence, $\lambda_s$ is expressed as

$$\lambda_s = A + B/(t_f - t_0),$$

where from our previous discussion $t_0 = 2t_{ox} = 35$ Å, and $A$ and $B$ are fitting constants. As shown in Fig. 8, the dotted curve represents the best fitting result of the $\lambda_s$ data in zone (C) with Eq. (3). From this fitting, we find $A=6.6 \times 10^{-6}$ and $B=4.7 \times 10^{-4}$ Å. Moreover, when crossing over from zone (C) to zone (B), $\lambda_s$ decreases abruptly at $t_f = t_{fc} = 90$ Å. The reason may be that when $t_f = t_{fc}$ the thickness of CoFeB film is thin enough that the lower boundary of the upper CoO$_x$ layer is about to touch the upper boundary of the inner CoO$_x$ layer. Note, that from Fig. 1, the former (or lower) boundary is about 25 Å below the top surface, and the latter (or upper) boundary is about 40 Å above the glass surface. Here, the thickness of the CoO$_x$ layer (with $0 \leq y \leq 1$) is slightly larger than that of the CoO$_x$(0.4 \leq x \leq 1). Therefore, in zone (B) of Fig. 8, we are actually illustrating the $\lambda_s$ behavior of CoO$_x$ instead of CoFeB. This is reasonable, since we have shown that the CoO$_x$ film (or layer) is ferromagnetic.

The $t_f$ dependence of $H_c$ of the as-deposited CoFeB film is shown in Fig. 9. This plot can also be divided into three parts. Part (a) in Fig. 9, where $0<t_f<50$ Å, corresponds to zone (A) in Fig. 8. As explained before, in this part we could not detect the hysteresis signal from VSM, and therefore $H_c$ is not defined. In part (b), we see the $H_c$ behavior of the CoO$_x$ film (or layer). By using the same criterion, $t_{fc}$ estimated from this set of $H_c$ data is about 88 Å, which agrees with what we found previously from Fig. 8. In part (c), $H_c$ of the CoFeB film roughly increases as $(1/t_f)$ increases. This means that the surface pinning effect, due either to the oxide layer or to the surface roughness, plays a role on $H_c$. In general, $H_c$ in Fig. 9 is low and in the range of 10–22 Oe. As mentioned previously, the “average grain size” ($D$) in the amorphous matrix of the as-deposited CoFeB film is quite small (i.e., $D \approx 224$ Å) [Fig. 2(a)]. That means $D$ is surely smaller than the exchange length ($L_{ex}$), which is about 350 Å, for CoFeB. Therefore, the crystalline anisotropy cannot

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**FIG. 7.** The saturation magnetization ($M_s$) was measured by VSM. The $M_s/M_f$ ratio is plotted as a function of CoFeB film thickness ($t_f$). $M_s$ of amorphous CoFeB bulk is equal to 1357 G.

**FIG. 8.** Magnetostriictions $\lambda_s$ as a function of CoFeB film thickness. The dash curve in zone (C) is the result based on the Néel formula.

**FIG. 9.** Coercivity $H_c$ vs the CoFeB film thickness ($t_f$).
be important here. The random anisotropy (over many grains) leads to the consistent result that \( H_c \) should be low, as observed in Fig. 9.

IV. CONCLUSION

We have made the Co\(_{78}\)Fe\(_{11}\)B\(_{11}\) films with \( t_f \) varied from 25 to 503 Å by the dc sputtering method. From the Auger-depth profile analysis, we could identify one CoO\(_x\) layer, about \( t_{ox} = 15 \) Å thick, on the top surface of the CoFeB film, and another, about \( t_{ox} = 20 \) Å thick, near the CoFeB/glass interface, where \( x \) is defined as Co/Cu, and \( 0.4 < x < 1 \). Due to the proximity effect between CoO\(_x\) and CoFeB, the CoO\(_x\) layer may be ferromagnetic with magnetization \( M_{ox} \). We have proven that the above statement is correct by fitting the \( M_s \) data of the CoFeB films with Eq. (2) and found that \( M_{ox} = 394 \) G. From x-ray and TEM measurements, we find that the major phase in the as-deposited CoFeB film is amorphous phase mainly. In order to suppress the crystalline phase, the optimal condition at RT is \( P_{Ar} = 5 \times 10^{-3} \) Torr. Since \( p \geq 100 \mu \Omega \) cm in general, the CoFeB film should contain the amorphous phase mainly. From the TCR measurement, we find that CoFeB film crystallizes in two steps; at \( T_{cr1} = 61^\circ C \) and \( T_{cr2} = 172^\circ C \), respectively. Both the \( \lambda_s \) vs \( t_f \) and the \( H_c \) vs \( t_f \) plots show the two-zone (or two-part) characteristics. The dividing line between zones (B) and (C) for \( H_c \) is at \( t_{fc} = 90 \) Å and that between parts (b) and (c) for \( H_c \) is at \( t_{fc} = 88 \) Å. Either in zone (C) or in part (c), we find the \( \lambda_s \) or the \( H_c \) behavior of CoFeB, while either in zone (B) or in part (b), we find the \( \lambda_s \) or the \( H_c \) behavior of CoO\(_x\).

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