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Influences of post-annealing and internal stress on magnetoresistance properties of $Ni_{80}Fe_{20}$ films①

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Abstract: $Ni_{80}Fe_{20}$ films with thickness about 54 nm were deposited on K9 glass and thermally oxidized silicon substrates at ambient temperature by electron beam evaporation with deposition rate about 1.8 nm/min. The as-deposited films were annealed at 350, 450 and 570 ℃ respectively for 1 h. After annealing at 570 ℃, the anisotropic magnetoresistance ratio(R_{AM}) of the films is greatly improved. It increases to 3% - 3.5% nearly about three times of that of the as-deposited films. The grain size increases with the annealing temperature and the [111] crystal orientation is obviously enhanced after annealing at temperature above 450 ℃. The internal stress in the films deposited on K9 glass is compressive and the resistance measurement shows that $R_{M\parallel}$ is larger than $R_{M\perp}$ in these films. However, in the films deposited at the same conditions but on oxidized silicon substrates, the internal stress is tensile and $R_{M\perp}$ is larger than $R_{M\parallel}$. The differences of $R_{M\parallel}$ and $R_{M\perp}$ in two series of specimens are discussed.

Key words: $Ni_{80}Fe_{20}$ film; annealing; internal stress; anisotropic magnetoresistance
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1 INTRODUCTION

NiFe films have been widely investigated because of their excellent magnetic properties such as high magnetoresistance, low coercivity and high magnetic permeability[1]. NiFe as an important magnetic material has been applied in magnetic and electronic devices such as magnetic recording heads, magnetoresistive sensors[2-4]. There are many factors which influence the anisotropic magnetoresistance ratio(R_{AM}) of NiFe films. In previous works, it was found that R_{AM} of NiFe films has much relation to film thickness, substrate temperature[2], deposition methods [5], ect. The appropriate seed layers can yield high R_{AM} and good magnetic properties[6-8]. Lee et al found that a thin NiFeCr seed layer can yield high R_{AM} of 3.2% for thin NiFe films[9]. Annealing treatment can also improve R_{AM} and magnetic properties of NiFe films markedly [3, 10]. Because an internal stress in the thin films affects the reliability and the magnetic properties, the stress and its evolution in NiFe films attract much attention[11-13]. Some researchers studied the internal stresses in permalloy films prepared with different deposition parameters and found that the stress can be reduced by the appropriate combination of deposition parameters[14]. Bruckner et al investigated the internal stress origin and evolution in NiFe thin films during annealing[15]. However, the influence of the internal stress on the magnetoresistance properties is not very clear. The aim of the present work is to study the influences of annealing temperature and internal stress in the films on the magnetoresistance properties of $Ni_{80}Fe_{20}$ films.

2 EXPERIMENTAL

$Ni_{80}Fe_{20}$ films with thickness about 54 nm were deposited on K9 glass(about 2 mm thick) and thermally oxidized silicon substrates at ambient temperature by electron beam evaporation with deposition rate about 1.8 nm/min. The base pressure was lower than 6×10^{-4} Pa. The size of the specimens was about 12 mm long and 5 mm wide. The as-deposited films were respectively annealed at 350, 450 and 570 ℃ in a vacuum lower than 3×10^{-3} Pa for 1 h. The anisotropic magnetoresistance ratios of the films were measured using a four-point probe technique. The microstructure and morphology of the films were determined by X-ray diffraction (XRD) and atomic force microscopy (AFM). Auger electron spectroscopy(AES) measurements were carried out to analyse the composi-

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tion of the NiFe films.

3 RESULTS AND DISCUSSION

3.1 Magnetoresistance

The saturation resistances measured by applying a magnetic field parallel and perpendicular to the sensing current are denoted as $R_{\parallel}$ and $R_{\perp}$ respectively. The anisotropic magnetoresistance ratio R_{AM} can be defined as[16]

$$R_{AM} = \frac{\Delta R}{R} = \frac{R_{\parallel} - R_{\perp}}{\frac{1}{3}R_{\parallel} + \frac{2}{3}R_{\perp}} \tag{1}$$

The resistances measured with and without magnetic field are denoted as $R(H)$ and $R(0)$. Then magnetoresistance ratio R_M is given by

$$R_M = \frac{R(H) - R(0)}{R(0)} \tag{2}$$

The values of parallel magnetoresistance ratio $R_{M\parallel}$ (the sensing current parallel to the magnetic field), perpendicular magnetoresistance ratio $R_{M\perp}$ (the sensing current perpendicular to the magnetic field) and R_{AM} are shown as a function of annealing temperature in Fig. 1. For the films deposited on K9 glass substrates, as-deposited and annealed, $R_{M\parallel}$ is larger than $R_{M\perp}$, while for the films deposited on thermally oxidized silicon substrates $R_{M\perp}$ is larger than $R_{M\parallel}$.

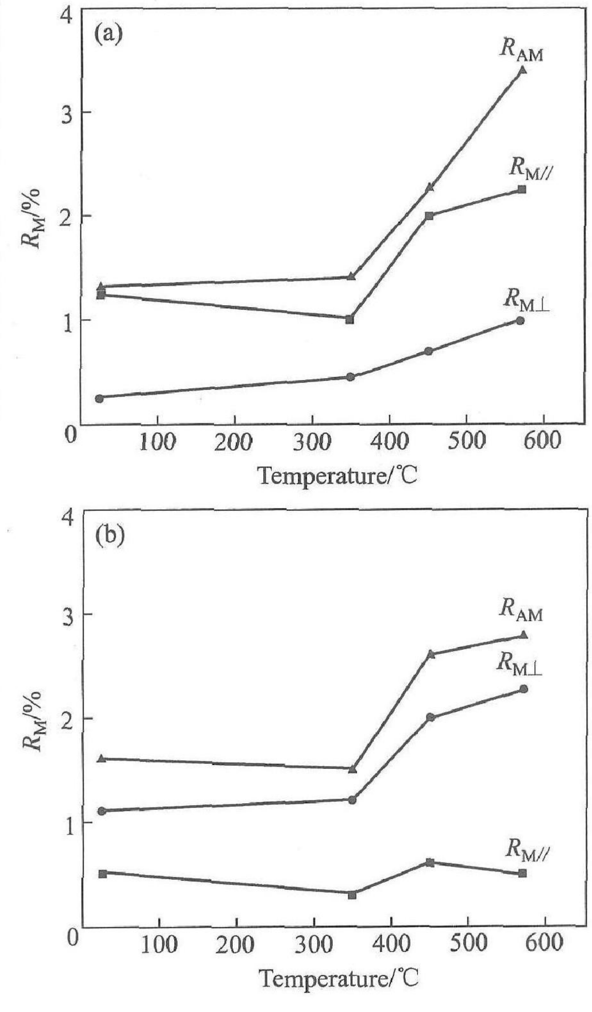

Fig. 1 $R_{M\parallel}$, $R_{M\perp}$ and R_{AM} for as-deposited and post-annealed NiFe films deposited on K9 glass substrates (a) and thermally oxidized silicon substrates (b)

It can also be seen from Fig. 1 that the values of R_{AM} of the films deposited on the two different kinds of substrates increase with annealing temperature increasing. After annealing at a temperature below 350 ℃, R_{AM} almost does not change compared with that of the as-deposited films. But after annealing at 570 ℃, R_{AM} is greatly improved. It increases to 3%-3.5% nearly about three times that of the as-deposited films. Furthermore, the R_{AM} sensitivity for magnetic field increases from about $7.5 \times 10^{-4}\%/(A \cdot m^{-1})$ for the as-deposited films to about $2.4 \times 10^{-3}\%/(A \cdot m^{-1})$ for 570 ℃-annealed films. It can be seen that high temperature annealing treatment can significantly improve R_{AM} and its magnetic sensitivity of the films.

3.2 Microstructure and internal stress

Fig. 2 shows the XRD patterns of the $Ni_{80}Fe_{20}$ films. From Fig. 2 it can be seen that the [111] crystal orientation is obviously enhanced after annealing at temperature above 450 ℃ and a weak

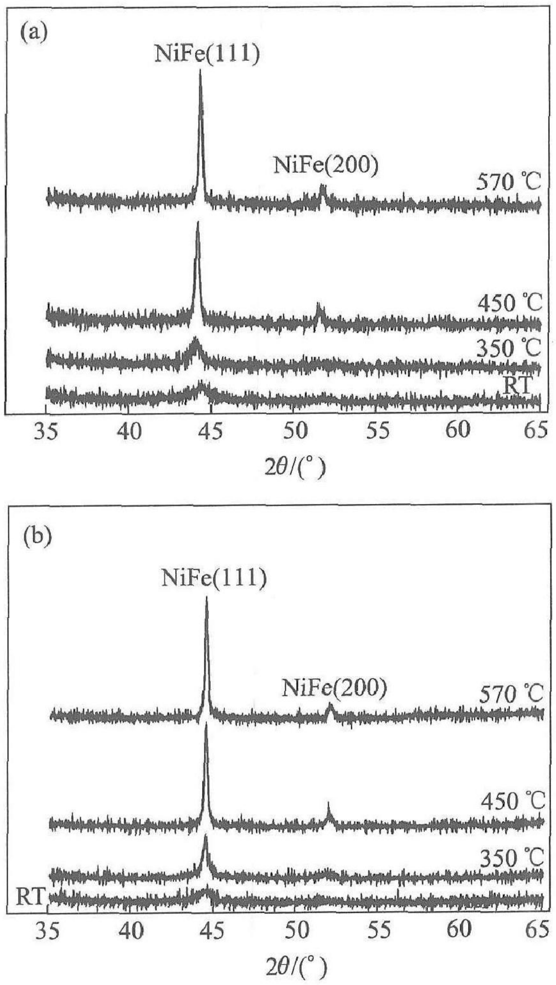

Fig. 2 XRD patterns of NiFe films deposited on K9 glass substrates (a) and thermally oxidized silicon substrates (b)

peak of (200) is observed. According to the results of the magnetoresistance measurements and the XRD patterns, it can be considered that R_{AM} of the NiFe films increases with the enhancement of the [111] texture. The grain size of the films was estimated from the full width at half maximum of XRD peaks of (111). It is found that the grain size increases from about 3 nm for the as-deposited films to about 6 nm for 570 ℃-annealed films. In conclusion, 570 ℃ post-annealing treatment can greatly improve the crystalline quality and the grain growth of the films.

The internal stress in the as-deposited and post annealed films can be analyzed from the data of XRD patterns. Under the assumption that the film remains elastic, the stress σ in the film can be calculated by the equation[15]

$$\sigma = \frac{E}{2\nu}\frac{L_0 - L}{L_0} \quad (3)$$

where E and ν are elastic modulus and Poisson's ratio of the film respectively; L is the lattice constant of the film which can be calculated by the data of XRD; L_0 is the lattice constant of NiFe bulk. For $Ni_{80}Fe_{20}$, E = 210 GPa. Also ν = 0.31 for Ni[15] was used as an estimate of ν for $Ni_{80}Fe_{20}$. The calculated stress in the films are listed in Table 1. $\sigma > 0$ indicates a tensile stress induced in the film while $\sigma < 0$ represents a compressive stress induced in the film.

Table 1 Values of internal stress σ for as-deposited and post-annealed NiFe films deposited on K9 glass substrates and thermally oxidized silicon substrates

Substrate	Annealing temperature			
	RT	350 ℃	450 ℃	570 ℃
K9 glass	− 0.450	− 2.662	− 1.484	− 0.172
Thermally oxidized silicon	1.705	0.986	0.986	1.120

From Table 1, it can be seen that the variations of σ in two series of films with the annealing temperature are different. In the films grown on K9 glass, a compressive stress exists while in the films grown on thermally oxidized silicon substrates a tensile stress exists.

The internal stress in the films may cause changes in the magnetic properties of the films. When $\lambda_s\sigma > 0$ (λ_s: spontaneous magnetostrictive coefficient), the spontaneous magnetic moment, M, rotates to the stress direction; when $\lambda_s\sigma < 0$, M tends to be perpendicular to the stress direction[16].

For $Ni_{80}Fe_{20}$, $\lambda_s > 0$[16]. The influence of stress σ on the spontaneous magnetic moment direction in two series of specimens are shown in Fig. 3. For the films deposited on K9 glass $\lambda_s\sigma < 0$ and M tends to be perpendicular to the stress direction while for the films deposited on thermally oxidized silicon substrates $\lambda_s\sigma > 0$ and M tends to be parallel to the stress direction.

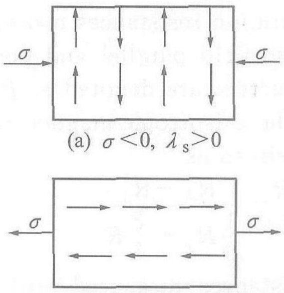

Fig. 3 Influence of stress σ on spontaneous magnetic moment direction in NiFe films deposited on K9 glass substrates (a) and thermally oxidized silicon substrates (b)

Dependence of anisotropic resistivity on the angle between sensing current and magnetic moment, ξ, can be expressed as[16]

$$\rho(\xi) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\xi \quad (4)$$

where $\rho_\parallel$ and $\rho_\perp$ are the saturation resistivities when the applied magnetic field parallel and perpendicular to the sensing current, respectively.

For the films deposited on thermally oxidized silicon substrates, $\lambda_s\sigma > 0$ and M tends to be parallel to the stress direction. If a sensing current is applied parallel to the stress direction and a magnetic field is applied parallel to the sensing current, ξ will change slightly or almost not change with the increase of the applied magnetic field resulting in a small value of $R_{M\parallel}$. While if the magnetic field is applied perpendicular to the sensing current, ξ will change from $\pi/2$ to 0 with the increase of the applied magnetic field and the value of $R_{M\perp}$ will be relatively large. Therefore $R_{M\perp}$ is larger than $R_{M\parallel}$ in these films. For the films deposited on K9 glass, because M tends to be perpendicular to the stress direction, the situation is just contrary to that of the films deposited on thermally oxidized silicon substrates. According to the above discussion, the different initial spontaneous magnetization direction causes $R_{M\parallel} > R_{M\perp}$ for the films grown on K9 glass and $R_{M\parallel} < R_{M\perp}$ for the films grown on thermally oxidized silicon substrate. And the different initial spontaneous magnetization direction is due to the different internal stress states in the two series of films.

3.3 Morphology

For the films deposited on K9 glass substrates and thermally oxidized silicon substrates annealed at the same temperatures the AFM microphotographs of film surface are similar. Fig. 4 shows the

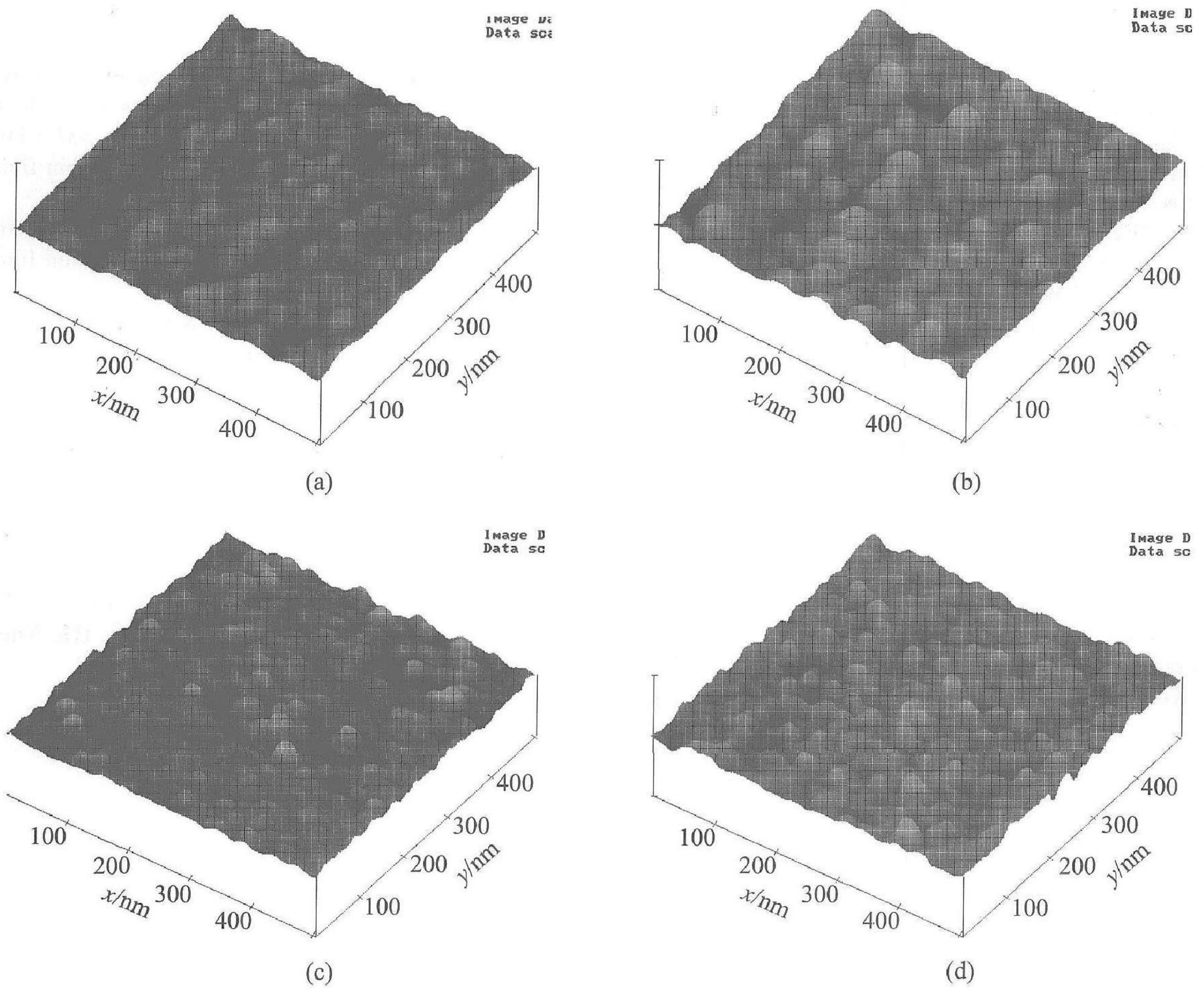

Fig. 4 AFM microphotographs of as-deposited and post-annealing NiFe films deposited on K9 glass substrates

(a) —RT; (b) —350 ℃; (c) —450 ℃; (d) —570 ℃

AFM microphotographs of the films deposited on K9 glass substrates. As seen in Fig. 4, the grain size increases after annealing at 350 ℃ while almost does not change after annealing at 450 ℃ and 570 ℃. AES analyses show that for the specimen annealed at 570 ℃, the contents of O and C at surface are much higher than that of the as-deposited one, however no obvious differences are shown in the contents of O, C, Ni and Fe in the film bulk for as-deposited and 570 ℃ annealed films. Therefore the surface morphology of the specimens annealed at high temperature shown by AFM may be the oxidized surface layer. The XRD patterns verify that the grain size increases with annealing temperature increasing.

4 CONCLUSIONS

$Ni_{80}Fe_{20}$ films with thickness about 54 nm were annealed at 350, 450 and 570 ℃ for 1 h respectively. It is found that after 570 ℃ post-annealing the R_{AM} of the $Ni_{80}Fe_{20}$ films can be greatly improved to 3% – 3.5%. The [111] crystal orientation is obviously enhanced after annealing at temperature above 450 ℃. The internal stress in the films deposited on K9 glass is compressive and $R_{M\parallel}$ is larger than $R_{M\perp}$. However in the films deposited at the same condition but on oxidized silicon substrates the stress is tensile and $R_{M\perp}$ is larger than $R_{M\parallel}$. The difference of $R_{M\parallel}$ and $R_{M\perp}$ in two series of specimens is due to the difference in the internal stress.

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