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Stress-impedance effects in sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films fabricated by Microelectromechanical Systems technique

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Abstract Sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine structure have been realized on silicon cantilever by Microelectromechanical Systems technique, and the stress-impedance (SI) effects have been studied in the frequency range of 1–40 MHz. Experimental results show that the values of SI ratio increase with the deflection and a large SI ratio of –24.1% at 5 MHz with the average tension stress 69.9 MPa and strain 0.048% is obtained in the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films, which shows attractive for the applications of strain sensors.

Introduction

Giant magneto-impedance (GMI) effect has been extensively studied in amorphous soft magnetic wires and ribbons since its discovery in 1992, due to their potential applications in magnetic field sensing and magnetic recording head. However, many device applications still require materials in thin film form, because thin film devices can be prepared by sputtering method and integrated with circuits easily. In recent years, a large GMI effect has been observed in soft magnetic films, sandwiched and multilayered films [1–3], which is very attractive for the applications of magnetic field sensors. In addition, a strain or pressure applied to the soft magnetic materials causes a large change in impedance of the soft magnetic materials, which is called the stress-impedance (SI) effect. Shen et al. [4] firstly reported the SI effect in negative magnetostrictive Co-based amorphous wire in 1997, where a SI ratio of 14% was obtained at 20 MHz with tensile stress of 14 MPa. Later, stress sensors based on the SI effect in amorphous soft magnetic wires have been constructed [5, 6]. However, only few results concerning the SI effect have been reported in soft magnetic films or multilayered films [7–10]. Here we first present the SI effect in the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine structure, which was fabricated on silicon cantilever by Microelectromechanical Systems (MEMS) technique.

Experimental

The film structure of the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine structure is shown in Fig. 1, where the top view is shown in Fig. 1a and the cross section in Fig. 1b. The sandwiched films are composed of an inner Cu layer and two outer amorphous FeCuNbCrSiB films with extended Cu layer electrodes. The width and thickness for each FeCuNbCrSiB films is 1 mm and 3.6 μm, respectively. The width and thickness of the Cu layer is 0.4 mm and 2 μm, respectively. The length of the sandwiched films is 21 mm, and the space between two serpentine lines is 1 mm.

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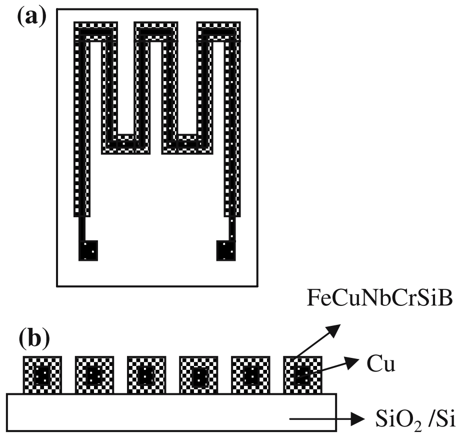
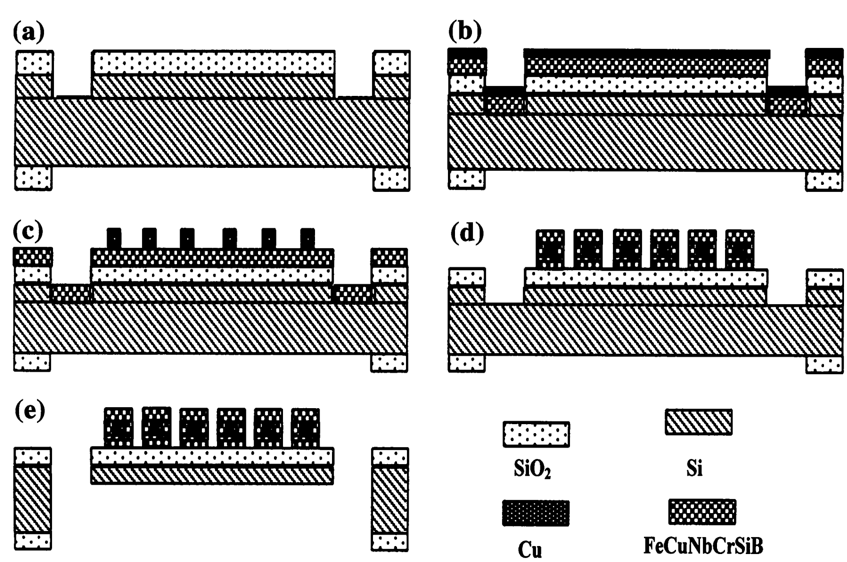


Fig. 1 Film structure of the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films, (**a**) top view and (**b**) cross section

The sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine structure were prepared on silicon cantilever by MEMS technique. The amorphous FeCuNbCrSiB film was deposited by magnetron sputtering, and the inner Cu layer was prepared by electroplating method. Before sputtering, the chamber was evacuated to below 1.2×10^{-4} Pa, and the sputtering conditions were selected to make a bulky FeCuNbCrSiB film in size of 26×72 mm^2 having an uniaxial magnetic anisotropy along the transverse direction, and the Argon pressure and sputtering power were 5.3 Pa and 600 W respectively. A constant magnetic field of 16 kA/m was applied along the transverse direction in the film plane during the deposition process. Fig. 2 shows the fabrication process of the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine structure on silicon cantilever by MEMS technique. The fabrication process started from a double oxidized 4-inches silicon wafer. (a) The double-side alignment symbols were formed which was very important for double-side mask alignment photolithography, where the SiO_2 layer with thickness of 2 μm was etched using the BHF solutions, and then the silicon cantilever structures were formed by etching the silicon substrates in thickness of 100 μm using the KOH solutions; (b) the FeCuNbCrSiB film was deposited with a thickness of 3.6 μm, and then the Cu seed layer with thickness of 80 nm was deposited by sputtering for electroplating the Cu layer; (c) photoresist was spin coated on the seed layer and patterned, and Cu layer was electroplated to the desired thickness, then photoresist and seed layer were removed with acetone and by RIE respectively; (d) the FeCuNbCrSiB film was deposited again, photoresist was spin coated on FeCuNbCrSiB film and patterned, the FeCuNbCrSiB film was etched using a specialized solutions, and then photoresist was removed, thus the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine line structure were formed; (e) formation of the silicon cantilever structures, the backside silicon was etched throughout using the KOH solutions, and a special clamp was adopted in order to protect the sandwiched films. Until now, the fabrication of the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine structure on silicon cantilever was finished.

The SI was measured by the HP4194A impedance analyzer with constant current amplitude of 10 mA and in the frequency range of 1–40 MHz. The stress in the sandwiched films was created by the cantilever structure as indicated in Fig. 3, where one end with two

Fig. 2 Fabrication process of the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films: (**a**) Etching of SiO_2 and Si; (**b**) deposition of FeCuNbCrSiB film and Cu seed layer; (**c**) photoresist spinning, pattern, electroplating the Cu layer; removal of photoresist and seed layer;(**d**) deposition of FeCuNbCrSiB film, photoresist spinning, pattern, etching of the FeCuNbCrSiB film and removal of photoresist; (**e**) backside etching of Si



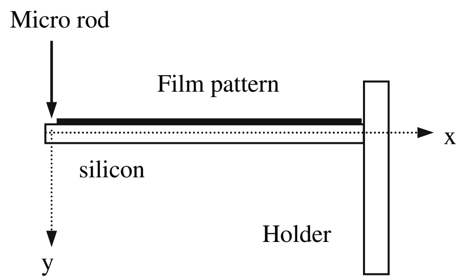


Fig. 3 The experimental setup for the evaluation of the stress impedance in the sandwiched films

extended electrodes is fixed and the deflection of the free end is controlled by a micrometer moving rod. During the measurements, no magnetic field was applied or heat treat was done.

Obviously the stress and strain in the films are not uniform. Due to the fact that the thickness of the films is much smaller than that of the silicon substrate, the strain in the films could be approximately estimated by that of the top face of the silicon substrate. According to the elastic theory, the deflection and strain in the silicon cantilever could be described as:

$$y(x) = \frac{Fx^3}{6\ EI} - \frac{Fl^2x}{2EI} + \frac{Fl^3}{3EI}, \varepsilon_x = -\frac{Fxy}{EI} \tag{1}$$

Where $I = \frac{1}{12} w\ t^3$

Here F is the force on the free end, w, t and l is the width, thickness and length of cantilever, respectively. The real length of the cantilever part is 15 mm.

Then the deflection at the free end was:

$$\delta = y(x = 0) = \frac{F{*}l^3}{3\ EI} \tag{2}$$

The strain in the films could respectively be expressed as:

$$\varepsilon_f = \varepsilon_x\left(y = -\frac{t}{2}\right) = \frac{3t\delta x}{2l^3} \tag{3}$$

And the average strain in the films is obtained:

$$\overline{\varepsilon_f} = \frac{\int_0^l \varepsilon_f \mathrm{d}x}{l} = \frac{3t\delta}{4l^2} \tag{4}$$

The elastic modulus of the sandwiched structure is evaluated in the form:

$$E_f = \frac{2E_m h_m + E_c h_c}{2h_m + h_c} \tag{5}$$

Then the average stress in the films could be calculated according to:

$$\sigma = E_f \varepsilon. \tag{6}$$

The Young's modulus of silicon and copper used is 159 and 115.2 GPa, respectively. Moreover the magnetic film was measured to be about 156.6 GPa by nanoindentation technique.

It could be observed that the average stress and strain in the films are proportional to the deflection of the free end. So in addition to the deflection, the average stress and strain are also specified in the X axis to clarify the variation in the films.

The SI ratio is defined as $\Delta Z/Z = 100\% * [|Z(x)| - |Z(0)|]/|Z(0)|$, where $|Z(x)|$ and $|Z(0)|$ are the SI corresponding to the deflection, average stress or strain value x and 0, respectively.

Results and discussion

Figure 4 shows the deflection, average stress and strain dependence of the SI ratio in the sandwiched films with a serpentine structure. One can see that the SI ratio is negative and increases monotonically in magnitudes with the increase of the deflection of the free end of the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films, and the maximum SI ratio of –24.1% is obtained at the deflection of 1.5 mm for a frequency of 5 MHz, which corresponds to the average stress and strain 69.9 MPa and 0.048%, respectively.

For the sandwiched films, having the outer magnetic layers with the conductivity σ_m and the thickness d_m,

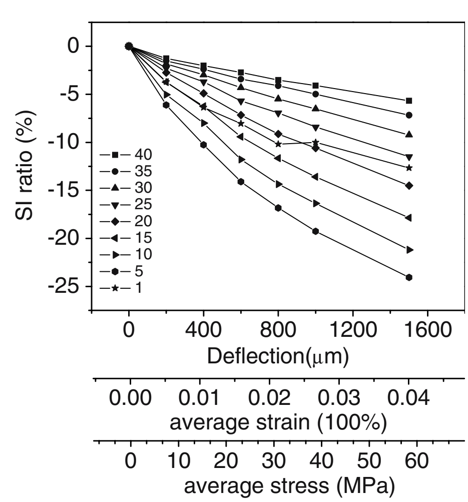


Fig. 4 Deflection dependence of the SI ratio in the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films

and the inner conductive layer with the conductivity $\sigma_c \gg \sigma_m$ and the thickness d_c, if the sandwich width b is sufficiently large, $b \gg 2\lambda = 2\ (d_m d_c \mu_{eff}/2)^{1/2}$, the leakage through the conductive layer of the magnetic flux induced by the current can be neglected. Then the solution for the impedance of a three-layer film infinite in two directions can be used. Its low-frequency expansion leads to the following: for $d_c\sigma_c/2 \gg d_m\sigma_m$ the inductive term proportional to effective transverse permeability μ_{ef} can give the main contribution to Z, even in the case of a weak skin effect. For this condition Z has a simple complex form [11]:

$$Z = R_c - j(2\pi\omega/c^2)(d_m/2b)l\mu_{ef}, R_c = l/2bd_c\sigma_c, \quad (7)$$

Here R_c is the resistance of the conductive layer, l is the film length, ω is the angle frequency of the ac current, c is the velocity of light (Gaussian units are used). It is a reasonable approach for our frequency and geometric dimension range.

Furthermore the magnetoelastic anisotropy $H_{\sigma k}$ could be expressed as:

$$H_{\sigma K} = \frac{2K}{\mu_0 M_S} = \frac{3\lambda_S(\sigma_{int} + \sigma_{appl})}{\mu_0 M_S} \quad (8)$$

Where K is the magnetoelastic anisotropy constant, λ_s is the saturation magnetostriction constant σ_{int} is internal stress in the films and σ_{appl} is applied stress, M_s the saturation magnetization. It could be found that $H_{\sigma k}$ indicated the increasing tendency with σ_{appl}.

In addition, the magnetoelastic energy could be expressed as:

$$E_\sigma = \frac{3}{2}\lambda_s\sigma \sin^2\theta \quad (9)$$

θ is the angular between applied stress and magnetization

When λ_s is positive and the film is in the state of tensile stress, to keep the magnetoelastic energy mimimum, the magnetization tends to be toward the direction of applied stress. As a result, with the rising deflection of the free end of the sandwiched films, the longitudinal magnetoelastic anisotropy increases and the permeability μ_{ef} decreases, which causes the decrease of the impedance.

Figure 5 shows the frequency dependence of the SI ratio at different deflections of the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films in tensile stress. It is clear from Fig. 5 that the SI ratio increases negative in magnitudes with the increase of frequencies, and reaches to a negative maximum value at a frequency of 5 MHz, and then decreases in negative values with the increase of frequencies. This could be explained according to the magnetization mechanism dominated in different frequency stages, which is similar to the behavior of GMI. The permeability μ_{ef} is composed of the domain wall χ_{dw} and moment rotation χ_{rot} contributions. Typically, χ_{dw} dominates at relatively low frequencies less than the characteristic relaxation frequency ω_{dw} of the domain-wall movement, whereas at higher frequencies χ_{rot} becomes important, since the relaxation is much faster in the case of rotational processes [11]. The maximum value of –24.1% at the deflection of 1.5 mm is obtained for a frequency of 5 MHz in the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films, which is useful for the applications of strain or pressure sensors.

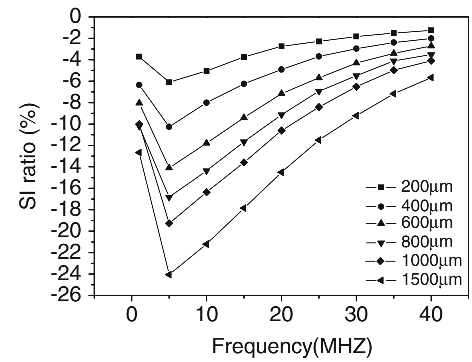


Fig. 5 Frequency dependence of the SI ratio in the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films

Conclusions

In conclusions, the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films with a serpentine structure were fabricated on silicon cantilever by MEMS technique, and the SI effects have been studied in the frequency range of 1–40 MHz. A large negative SI ratio of –24.1% at a frequency of 5 MHz with the deflection of 1.5 mm, which corresponds to the average stress and strain 69.9 MPa and 0.048%, respectively is obtained in the sandwiched FeCuNbCrSiB/Cu/FeCuNbCrSiB films, which is attractive in constructing new strain or pressure sensor.

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