MAGNETOSTRICTIVE DELAY LINE THIN FILMS AS SENSING ELEMENTS

E. Hristoforou, K. Kosmas, E. Gravvanis, DM Kepaptsoglou, N. Kontos

Laboratory of Physical Metallurgy, National Technical University of Athens, 9, Heroon Polytechniou Str., Zographou Campus, Athens 15780, Greece, Phone (301) 7722178, Fax (301) 7722119, e-mail: eh@metal.ntua.gr

Abstract - *A miniaturized arrangement based on magnetostrictive delay line (MDL) mechanism, able to be used as sensor, is realized using thin films technology. In order to obtain high-performance miniaturized magnetostrictive delay line arrangement we used Fe, Ni and $Fe_{70}B_{20}Si_6C_4$ amorphous thin films as magnetostrictive sensing element because of their better magnetic and magnetoelastic characteristics than conventional magnetostrictive thin films. A monolithic design has been achieved with the electric equipment and sensing element contained onto the same silicon substrate.*

Keywords - Sensors, thin films, magnetostriction

1. INTRODUCTION

Magnetoelastic (ME) sensing applications are usually based on the magnetostrictive materials, ribbon and wire shaped, with high magnetostriction compositions exploiting their magnetoelastic (ME) properties [1]. In the last years, a great emphasis has been placed on the examination of the magnetoelastic (ME) effects in thin films, considering that these effects are promising sensing mechanisms for magnetomechanical microsensors [2,3,4]. The most relevant parameters, which determine the performance of the magnetomechanical sensors are ME coupling factor $k=\Delta E/E$, a basic index of sensor energy conversion capability, defined as fractional change of the Young's modulus, E, obtained by magnetization, magnetostriction $\lambda=dl/l$, fractional increase in length obtained by magnetization, and magnetostrictive strain coefficient $d=d\lambda/dH$, rate at which the strain is developed with respect to the applied field [5]. The importance of these parameters depends on the kind of ME sensing application. For the ME microsensors obtained using thin films technology, where power and physical size are important factors in designing, the magnetostrictive strain coefficient d has the same importance as ME coupling factor k. Generally, the magnetic properties of magnetostrictive thin films are very sensitive to the presence of stresses developed during the deposition process of thin films. On the other hand, independent by the method of deposition, the stresses generated by the difference of the thermal expansion and/or the thermal contraction during the preparation and lattice mismatch are dependent on the material substrate. The ME properties of thin films are modified by the mechanical properties of the substrate, due to the strong interaction between substrate and film, the substrate transmitting or receiving the strain induced by applying a magnetic field. Knowing the saturation magnetostriction constant λ_s, which describes the ME effect in bulk samples, is not sufficiently to anticipate the performance of the microsensors. If the isotropic thin film is sufficiently thick (surface magnetostriction is negligible) a single ME coupling coefficient $b^{\gamma,2}$ is necessary to describe the ME effects in active-magnetoelastic thin film medium. For applications using the change of the magnetic properties of materials for sensing displacement, force and torque, a combination of magnetic and ME properties is usually required (i.e. low values of anisotropy field H_k, high values of saturation magnetization $4\pi M_s$ and high values of ME properties) [6]. In order to obtain magnetoelastic thin films media having optimum ME properties, Fe-metalloid amorphous thin films and multilayered structures based on FeCo/Ag deposited onto different substrates have been used [7].

2. THE MINIATURIZED MDL ARRANGEMENT

The schematic arrangement of the miniaturized MDL on a silicon wafer using a multilayer-like structure X/Y/X, where X is a multilayer structure of $SiO_2/Cu/SiO_2$ type and Y is the magnetostrictive material used as delay medium, is presented in Figure 1. This miniaturized MDL arrangement using Fe-based amorphous thin film as sensing element is produced using the standard technological processes. Previously described technological solution, although offering high level of sensitivity, is not an easy procedure concerning the flux change receiving means, adding possible difficulties in the reliability of the sensing element. Alternatively, the flux change sensing means is realized using the arrangement illustrated in Figure 2. According to this, a $Ni_{81}Fe_{19}/SiO_2/Ni_{81}Fe_{19}$ three-layered MR structure is arranged bellow the $Fe_{70}Si_{15}B_{15}$ thin film, separated by a silicon dioxide layer. Another thin film layer made of $Fe_{70}Si_{15}B_{15}$ amorphous alloy, is deposited below the three-layered MR structure, in order to increase the sensitivity of the flux change detection. The insulating layers and $Fe_{70}Si_{15}B_{15}$ amorphous thin films were deposited by r.f. sputtering method. The $Ni_{81}Fe_{19}$ thin films (about 0. 05 μm in thickness) were deposited by electron beam vacuum evaporation method.

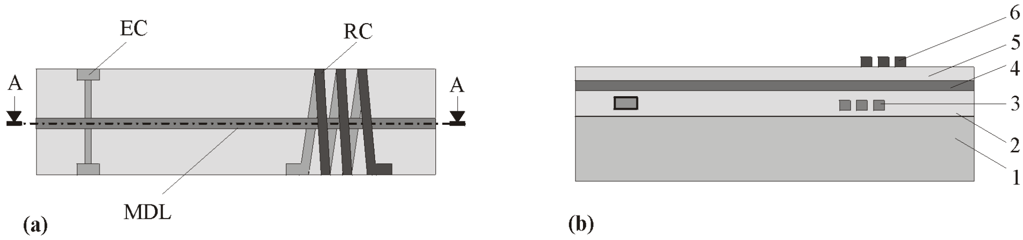

Figure 1. The miniaturized arrangement of the MDL fabricated by thin film technology: (a) top view of the complete packaged thin film magnetostrictive delay line; (b) cross sectional view A - A: 1 - thin film wafer; 2 - insulating layer; 3 - first layer of Cu; 4 - $Fe_{70}B_{15}Si_{15}$ amorphous thin film operating as MDL medium; 5 - insulating layer; 6 - last layer of Cu.

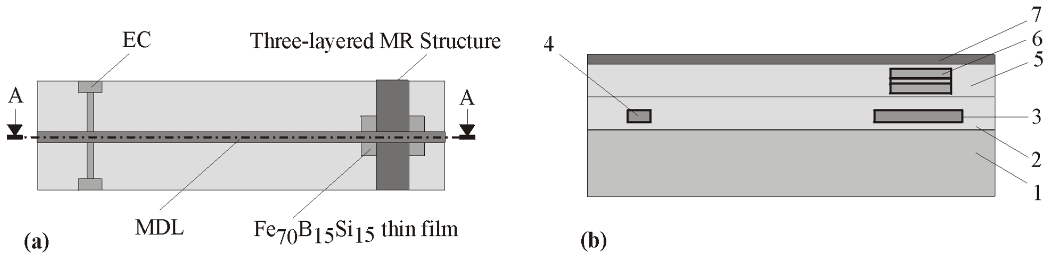

Figure 2. The miniaturized arrangement of MDL fabricated using a multilayer-like structure: (a) top view of the complete multilayer-like structure; (b) cross sectional view A - A: 1 - thin film wafer; 2 - insulating layer; 3 - $Fe_{70}B_{15}Si_{15}$ amorphous thin film; 4 - Cu thin film; 5 - insulating layer; 6 - three-layered MR sensing structure; 7 - $Fe_{70}B_{15}Si_{15}$ amorphous thin film operating as MDL medium.

3. EXPERIMENTS

The three-layered MR sensing structure with a 5 × 0.05 mm^2 rectangular shape is presented in Figure 3. The non-linear output in the applied magnetic field is avoided by applying a bias field in the perpendicular direction to easy axis. Thus, the angle between magnetization and current direction is maintained at 45° and the response of the $Ni_{81}Fe_{19}$ thin film to the magnetic field becomes linear. The bias field was achieved using soft adjanced layer (SAL) biasing scheme.

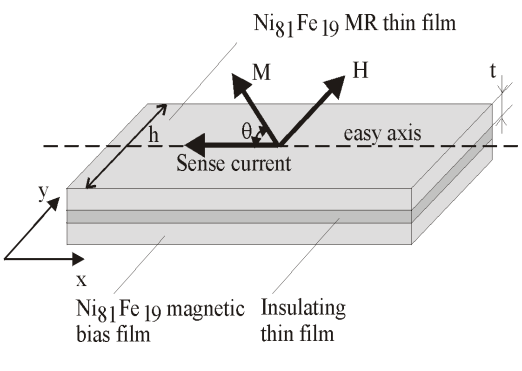

Figure 3. The three-layered MR structure based on $Ni_{81}Fe_{19}/SiO_2/$ $Ni_{81}Fe_{19}$ thin films used for flux change sensing in the miniaturized MDL arrangement.

In SAL biasing, a $Ni_{81}Fe_{19}$ thin film is placed adjacent to the first $Ni_{81}Fe_{19}$ thin film and separated by a SiO_2 thin film with a thickness of 500 Å. The easy axis of the magnetic bias $Ni_{81}Fe_{19}$ thin film is in the y direction, perpendicular to easy axis of the first MR $Ni_{81}Fe_{19}$ thin film. The magnetic field generated by the current flowing in the $Ni_{81}Fe_{19}$ MR thin film magnetizes the soft magnetic $Ni_{81}Fe_{19}$ thin film up to the saturation. The SAL, in turn, produces the field which biasis the MR thin film. An uniaxial anisotropy was easily induced by depositing $Ni_{81}Fe_{19}$ thin film in a weak magnetic field of about 100 Oe, applied in the film plane. The response of the three-layered MR structure used in miniaturized MDL arrangement at the magnetoelastic waves which propagate in MDL is under investigation.

In order to obtain ME thin film medium, with optimum properties for magnetomechanical microsensors, the ME properties (ME coupling coefficient $b^{\gamma,2}$, saturation magnetostriction constant λ_s and magnetostrictive strain coefficient d) of the conventional magnetostrictive and amorphous Fe-metalloid thin films deposited on various substrates have been investigated.

We prepared Ni thin films, 7560 Å thickness, using electron beam evaporation technique and also Fe-based amorphous thin films, 5460 Å thickness, using a r.f. sputtering method. In one experimental run, three substrates of glass, mica and silicon were coated simultaneously. The thickness of the thin films was monitored during deposition by a quartz-crystal system and verified by microweighing method. We have utilized glass substrates for magnetic measurements and silicon and mica substrates for magnetostrictive measurements.

The saturation magnetostriction and ME coupling coefficient for Ni and amorphous $Fe_{70}B_{20}Si_6C_4$ thin films deposited onto silicon and mica cantilever-substrate were measured using capacitive-cantilever technique [8]. The sign and magnitude of magnetostriction and ME coupling coefficient were determined using an experimental set-up based on this technique [9].

We have made static measurements of the longitudinal $\delta_{||}$ and transversal $\delta_{\perp}$ deflection of the free end of a rectangular bimorph (magnetic thin films and non-magnetic substrate), clamped in cantilever configuration, as a function of the external magnetic field.

The Curie temperature T_C, saturation magnetization M_s and magnetic anisotropy field H_k are forming a triad of magnetic characteristics which in combination with magnetoelastic characteristics (saturation magnetostriction λ_s, magnetoelastic coupling coefficient $b^{\gamma,2}$, magnetoelastic coupling factor k and ΔE-effect) determine the performance of the material used as sensing element for miniaturized MDL arrangement.

Among the crystalline materials, nickel thin film is a good one as sensing element for miniaturized MDL arrangement. Various experiments show that the magnetomechanical coupling factor k and ΔE-effect for $Fe_{81}B_{13.5}Si_{3.5}C_2$ amorphous alloy have larger values in comparison with nickel or any other magnetostrictive material. It has been established that the magnitude of the ΔE-effect depends on the ratio between the saturation magnetostriction constant λ_S and the magnetic anisotropy constant k_u. If E_s is the Young's modulus in magnetically saturated state and E is the Young's modulus in magnetically unsaturated state, the following equation gives information on the possibility of maximum changes of the sound velocities or the time of the signal delay for different materials used as sensing elements:

$$\frac{E}{E_s}_{\min} = \left(1 + \left(\frac{9\lambda^2{}_s E_s}{2k_u}\right)\right)^{-1} \quad (1)$$

The study of the magnetic and magnetoelastic properties of Fe-based amorphous thin films shows that they exhibit ideal characteristics for magnetostrictive delay line medium.

Another advantage of the use of amorphous thin films as magnetoelastic sensing element, applicable for the wide-range position sensors, is the large distance through which magnetoelastic wave propagates. This advantage arises as the effect of the high electrical resistivity of amorphous thin films, resulting in low eddy current losses and low value of the attenuation constant of the propagated magnetoelastic waves.

4. DISCUSSION

We used the formulas derived by E. du Tremolet de Lacheisserie and Peuzin [10] to determine the saturation magnetostriction λ_s and ME coupling coefficient $b^{\gamma,2}$ for Ni and $Fe_{70}B_{20}Si_6C_4$ thin films. In order to perform such experiments, commercially available standard silicon and mica substrates with $40\times5\times0.3\text{mm}^3$, $60\times10\times0.45\text{mm}^3$ and $40\times5\times0.25\text{mm}^3$, $60\times10\times0.25\text{mm}^3$ rectangular form, respectively, have been coated on one side with magnetostrictive materials. The film-coated substrates were rigidly clamped at one end in a cantilever configuration with the film surface acting as one plate of a parallel capacitor.

Considering that the magnetostrictive films are sufficiently thick and the substrate is much thicker than film, the following expressions relate the saturation magnetostriction λ_s, longitudinal magnetostriction $\lambda_{||}$, transversal magnetostriction $\lambda_{\perp}$ and ME coupling coefficient $b^{\gamma,2}$ of the thin films to the longitudinal $\delta_{||}$ and transversal $\delta_{\perp}$ deflections of the rectangular bimorph clamped in cantilever configuration [10]:

$$\frac{2}{3}(\lambda_{II} - \lambda_{\perp}) = \lambda_s = -\frac{2}{9} \cdot \frac{\delta_{II} - \delta_{\perp}}{L^2} \cdot \frac{E_0 \cdot h_0^2 \cdot (1+\nu_f)}{E_f \cdot h_f .(1+\nu_0)} \quad (2)$$

and

$$(b^{\gamma,2})_f = \frac{G_0(\delta_{II} - \delta_{\perp})h_0^2}{3L^2 h_f} = b(H) = b_{II} - b_{\perp} \quad (3)$$

In Eqs. (2) and (3) we used the index "f" for thin film and "0" for substrate. Taking into account that the demagnetized state of thin films is generally anisotropic, it is easily accessible to measure the deflection of the cantilever along Ox direction, in (xOz) plane, first applying the magnetic field in the film plane (xOy) along the length of the cantilever (Ox) - $\delta_{||}$ and then along the width of sample (Oy) - $\delta_{\perp}$ (see Figure 1).

When use Eqs. (2) and (3) to determine the saturation magnetostriction and the ME coupling coefficient of thin films, the elastic constants values (the Young's modulus E, the Poisson'ratio ν, and shear coefficient G) of the cantilevered substrate and thin film are needed but these have not generally measured. Although using estimated values for the elastic constants of the Ni thin films (E_f = 1.92×10^{12} dynes/cm^2, $\nu_f = 0.34$), the silicon ($E_0 = 1.9\times10^{12}$ dynes/cm^2, $\nu_0 = 0.09$) and mica ($E_0 = 2.1\times10^{12}$ dynes/cm^2, $\nu_0 = 0.25$) substrates, the measured values of the saturation magnetostriction constant for Ni thin films are in good agreement with the values reported for these samples from other techniques [11].

The linear longitudinal and transverse magnetostriction dependences of the investigated samples (5460 Å-sputtered $Fe_{70}B_{20}Si_6C_4$ and 6750 Å-evaporated Ni thin films onto silicon substrates) on the external magnetic field: The

saturation magnetostriction for $Fe_{70}B_{20}Si_6C_4$ and Ni thin films can be estimated as $\lambda_s = 34 \times 10^{-6}$ and $\lambda_s = -31\times10^{-6}$, respectively.
The static $\lambda_{||}$ - H and $\lambda_\perp$ - H curves of (a) $Fe_{70}B_{20}Si_6C_4$ and (b) Ni thin films deposited on the mica substrate were measured. The saturation magnetostriction for $Fe_{70}B_{20}Si_6C_4$ and Ni thin films can be derived from static $\lambda_{||}$ - H and $\lambda_\perp$ - H curves. So, $\lambda_s = 30 \times 10^{-6}$ and $\lambda_s = -29 \times 10^{-6}$, respectively. The accuracy of this tool for measuring the saturation magnetostriction of thin films is difficult to assess because there is no standard to compare. Many measurements can be run on the same specimen, allowing to check the reproducibility of the experiments. Such reproducible mesurements also allow to quantify the accuracy of the mesurements. The reproducibility of λ_s is better than 3%.
The calculated values of λ_s for $Fe_{70}B_{20}Si_6C_4$ amorphous thin films agree with the values previously reported for Fe-based amorphous thin films [12].
It can be concluded that $Fe_{70}B_{20}Si_6C_4$ and Ni thin films deposited on mica substrates required higher magnetic fields to be saturated (1800 G and 3600 G) than the same thin films deposited on silicon substrates (900 G and 2200 G). This difference was caused by large internal compressive stresses in $Fe_{70}B_{20}Si_6C_4$ thin films with positive magnetostriction and by large internal tensile stresses in Ni thin films with negative magnetostriction deposited onto mica substrate. The explanation probably lies in the fact that these large internal stresses are caused not only by the difference between the thermal expansion coefficients of mica substrate ($\alpha_0 = 36 \times 10^{-6}$ °C^{-1}) and layer ($\alpha_f = 5.2 \times 10^{-6}$ °C^{-1} for Ni and $\alpha_f = 7.9 \times 10^{-6}$ °C^{-1} for amorphous alloy) but also by the lattice mismatch of the layer and mica substrate, deposition processes and reactions and phase transformations.
The magnetostrictive strain coefficient defined as the ratio of the linear magnetostriction to the magnetic field, i.e. $d = \lambda/H$, was calculated from the static magnetostriction curves similar to the permeability calculated from the static magnetization curves. The maximum magnetostrictive strain coefficient values were determined from the slope of the static $\lambda_{||}$ - H curves for Ni and $Fe_{70}B_{20}Si_6C_4$ thin films deposited on silicon and mica substrates. The $Fe_{70}B_{20}Si_6C_4$ thin films deposited on the silicon substrate exhibit the highest values of the magnetostriction strain coefficient, $d = 425 \times 10^{-10}$ G^{-1}, for a magnetic field equal to 700 G. The Ni thin films deposited on the mica substrate exhibit the lowest values of the magnetostriction strain coefficient, $d = 195 \times 10^{-10}$ G^{-1}, for a magnetic field equal to 2400 G.
Considering the obtained values of magnetostriction strain coefficient for magnetostrictive thin films deposited on different substrates, we found that the silicon is the most suitable material as substrate for magnetoelastic medium having better low-magnetostriction properties.
The b(H) function defined as ($b_{||}$ - $b_\perp$), in analogy to ($\lambda_{||}$ - $\lambda_\perp$) = $\lambda^{\gamma,2} = 3\lambda_s/2$, for $Fe_{70}B_{20}Si_6C_4$ and Ni thin films when deposited on the silicon and mica substrates, respectively.
Notable changes in the values of ME coefficients were observed in lower-field region (up to 900 G) for $Fe_{70}B_{20}Si_6C_4$ thin films sputtered on silicon substrate than for $Fe_{70}B_{20}Si_6C_4$ thin films sputtered on mica substrate. This magnetoelastic behaviour of the samples deposited on silicon substrate is of essential interest for magnetomechanical applications in microsensors technology.
Our results on saturation magnetostriction λ_s, ME coupling coefficient $b^{\gamma,2}$ and magnetostriction strain coefficient d for Ni and $Fe_{70}B_{20}Si_6C_4$ thin films deposited onto silicon and mica substrates were correlated to the magnetic properties of technical significance for these thin films used as magnetoelastic media for magnetomechanical microsensors.
Since the values of the saturation magnetostriction and ME coupling coefficient are approximately the same for Ni crystalline and amorphous thin films, the first sample exhibits a considerably smaller value of the saturation magnetization and a larger value of the anisotropy constant than the second. The results show that amorphous thin films deposited on silicon substrate exhibit better magnetic and magnetoelastic properties than those of Ni thin films to achieve magnetomechanical sensors with high performances.

CONCLUSIONS

We have demonstrated that the relevant properties of the magnetoelastic thin films media used for magnetomechanical microsensors can be considerably improved using amorphous Fe-metalloid thin films sputtered on silicon substrates in comparison with the conventional magnetostrictive thin films evaporated on silicon and mica substrates.
The assessment and control of ME properties of the thin films deposited onto various substrates are adding to the knowledge of their magnetic properties and could lead to achieve magnetomechanical thin film-microsensors with high performances.

Thickness (Å)	T_C (°C)	σ_s (emu/g)	$\lambda_s\times10^{-6}$	K_u (erg/g)	$b^{\gamma,2}\times10^6$ dynes/cm^2	D × 10^{-10}G^{-1}	ΔE/E
9500	338	132	32	2×10^3	-30	425	0. 58

Table 1. The values of the relevant parameters for sensing element performance of $Fe_{70}B_{20}Si_6C_4$ amorphous thin films: Curie temperature T_C, saturation magnetization σ_s, saturation magnetostriction λ_s, anisotropy constant k_u, magnetoelastic coefficient coupling $b^{\gamma,2}$, static stress-sensitivity D and ΔE-effect.

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