Trial on-silicon micromagnetoelastic devices

著者	石山　和志
journal or publication title	Journal of Applied Physics
volume	83
number	11
page range	7303-7305
year	1998
URL	http://hdl.handle.net/10097/47804

doi: 10.1063/1.367759

Trial on-silicon micromagnetoelastic devices

M. Takezawa, M. Yamaguchi, K. Ishiyama, and K. I. Arai
Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan

This paper discusses two new kinds of micromagnetoelastic devices made on silicon wafer whose function is to control the permeability of magnetostrictive soft magnetic thin films by voltage-controlled elastic strain. One is piezoelectric type and the other is electrostatic type. Structure, fabrication process, characteristics, and maximum possible output are discussed. The feasibility of these devices has been clarified although the rate of obtained permeability change was less than 1%. These device characteristics could be improved to 11% for piezoelectric type and to 80% for electrostatic type by the optimization of device dimensions and reduction of process damage to the magnetic film. © *1998 American Institute of Physics.* [S0021-8979(98)41311-2]

I. INTRODUCTION

Magnetostrictive thin-film materials are of current interest for microfabricated sensors,[1] actuators,[2,3] magnetosurface acoustic wave (MSAW) devices,[4] etc. A potential benefit of these devices is the capability of silicon integrated intelligent systems. However, little work has been reported on the combination of magnetostrictive films and silicon.[3]

Therefore, this paper discusses two new kinds of micromagnetoelastic devices made on a silicon wafer whose function is to control the permeability of magnetostrictive soft magnetic thin film by voltage-controlled elastic strain. One is piezoelectric type and the other is electrostatic type.

The piezoelectric type is the extension of our previous work[1] that used FeSiB film and bulk PZT. In this work we microfabricated a FeSiB/ZnO double layer film structure on a silicon membrane. The electrostatic type utilizes bending of FeSiB film-substrate beam caused by electrostatic force. The space to bend is formed by anisotropic etching of silicon. Feasibility of these devices is demonstrated in this paper.

II. FILM MATERIALS

A. Magnetostrictive FeSiB film

The 0.5 μm thick $Fe_{77}Si_{11}B_{12}$ amorphous film was rf-sputter deposited onto a surface oxidized (100) orientated silicon wafers. The Ar gas pressure was 3.3 Pa and the rf power was 100 W (5.7×10^2 W/m^2.) The as-deposited film had saturation magnetostriction of 33×10^{-6}, Curie temperature of 703 K, and a crystallization temperature of 743 K. These are similar to the published values.[5]

The stress release annealing without magnetic field was applied up to 673 K at below 2.7×10^{-4} Pa, which resulted in a remarkable coercive force decrease from 1990 A/m to 32 A/m and a permeability increase from 90 to 2300, as shown in Fig. 1. Then the films were annealed again in a static magnetic field of 39.8 kA/m at below 8.0×10^{-4} Pa for 2 h in order to stabilize the uniaxial anisotropy. The anisotropy field was increased from 200 to 280 A/m, and the squareness ratio, M_r/M_S along easy axis of magnetization was improved from 0.9 to nearly unity.

B. ZnO piezoelectric film

A 1 μm thick ZnO film was rf-sputter deposited on a surface oxidized (100) orientated silicon wafer using Ar: $O_2=8:2$ mixture gas. The total gas pressure was 4.0 Pa. The rf power was 100 W (5.7×10^2 W/m^2) and the substrate temperature was 473 K. The x-ray diffraction pattern of the film showed that the c axis was perpendicular to the film plane and its dispersion was 4 degrees. Since the threshold c-axis dispersion to degrade the piezoelectric properties is 6 degrees,[6] crystal orientation of the fabricated ZnO film is adequate for the proposed sensors. The resistivity was 4×10^9 Ωcm, which is similar to the published values.[7,8]

The piezoelectric constant d_{31} was measured using a Au(0.4 μm)/ZnO(3 μm)/Cr(0.5 μm) multilayer film rf-sputtered on (100) oriented silicon wafer. The Cr and Au films were used as electrodes. The measured strain was almost proportional to the applied dc voltage of ±2 V as shown in Fig. 2. The readout of d_{31} was -5×10^{-12} m/V, which is similar to the published values.[6]

C. FeSiB/ZnO double layer film

Figure 3 shows the annealing temperature dependence of initial permeability of FeSiB film deposited on the 1 μm thick ZnO film substrate. The as-deposited FeSiB film on ZnO film had permeability higher than single layer FeSiB

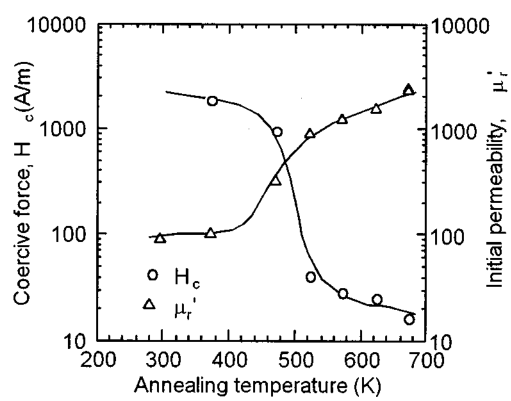

FIG. 1. Annealing temperature dependence of coercive force and permeability.

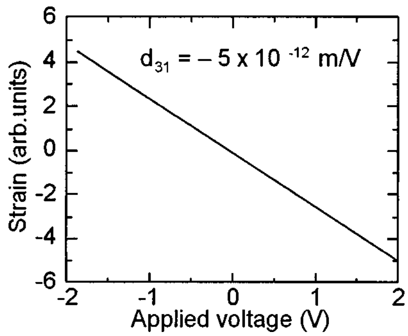

FIG. 2. Applied voltage dependence of ZnO strain.

film because of tensile stress given by the ZnO under layer. With raising the annealing temperature, the permeability reached 1000 at 673 K and was further enhanced to 1500 by static magnetic field annealing of 39.8 kA/m at below 8.0 $\times 10^{-4}$ Pa for 2 h. The value obtained is slightly degraded compared to the single layer FeSiB film but still compatible to that.

III. PIEZOELECTRIC TYPE DEVICE

Figure 4 shows the schematic view of the magnetostrictive-piezoelectric type microdevice. A 0.5 μm thick SiO_2 under layer, 0.5 μm thick FeSiB film, 0.5 μm thick Cr electrode layer, 6.5 μm thick ZnO piezoelectric film, 3 μm thick SiO_2 over layer and 2 μm thick Cr electrode layer were rf-sputter deposited in turn onto the (100) oriented silicon wafer. The main parts are FeSiB/ZnO double layers of 12 mm$\times$13 mm rectangle area. Then the wafer was anisotropically etched from the back side in tetramethyl ammonium hydroxide (TMAH) to form a 15 μm thick membrane.

Applying a voltage between the top and the bottom Cr electrode layers, a strain is produced in the ZnO film perpendicular to the film plane by inverse piezoelectric effect. The in-plane component of the strain causes in-plane strain to the FeSiB film, which controls the permeability of FeSiB film by the inverse magnetoelastic effect. The neutral plane of elastic strain is in the Si membrane. Positive applied voltage yields permeability decrease and negative voltage results in perme-

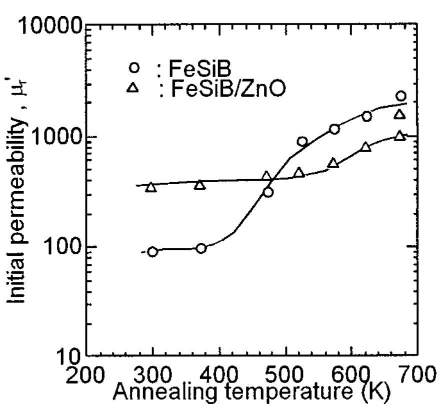

FIG. 3. Annealing temperature dependence of permeability of FeSiB/ZnO double layer film.

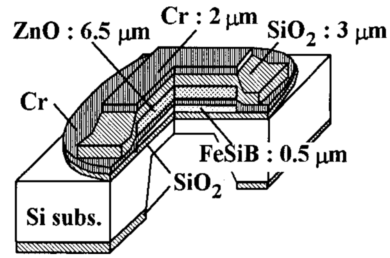

FIG. 4. Structure of micromagnetorestrictive-piezoelectric device.

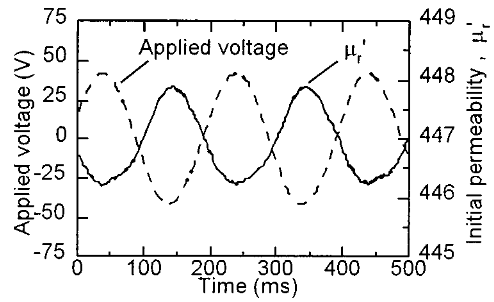

FIG. 5. Time variation of permeability for piezoelectric type device.

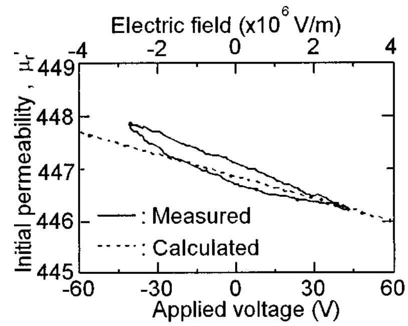

FIG. 6. Permeability vs applied voltage relationship for piezoelectric type device.

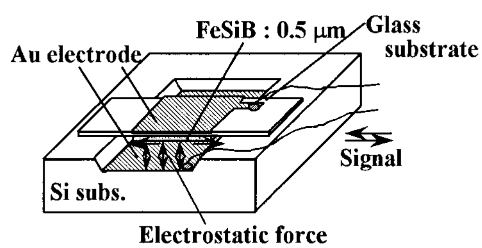

FIG. 7. Structure of micromagnetorestrictive-electrostatic type device.

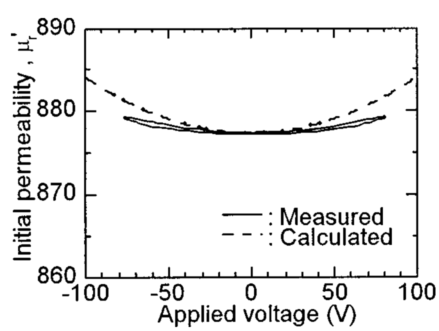

FIG. 8. Permeability vs applied voltage relationship for electrostatic type device.

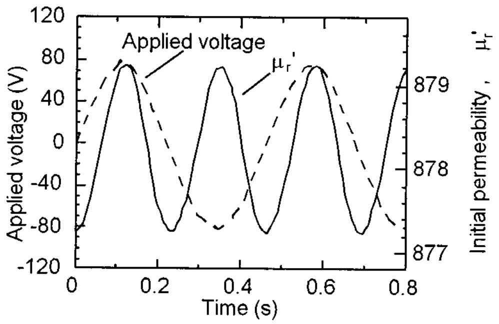

FIG. 9. Time variation of permeability for electrostatic type device.

ability increase because the sign of piezoelectric constant, d_{31}, is negative as showed in Fig. 2. Figure 5 is the experimental verification that a 5 Hz, $\pm 30\ V_{\rm rms}$ ($\pm 2\times 10^6$ V/m) sinusoidal voltage yielded the in-phase permeability change.

Theoretical permeability change is given by the following equation:

$$\mu_r' = M_s^2/[\mu_0\{2K_\mu - 3\lambda_s E(\Delta l/l)\}], \tag{1}$$

$$\Delta l/l = z/R, \tag{2}$$

where M_s is the saturation magnetization, K_u the anisotropy constant, E the Young's modulus, λ_S the saturation magnetostriction, z the distance from the neutral plane of elastic strain, and R the radius of film curvature. The film curvature and the position of neutral plane are determined by the thickness and Young's modulus of each of seven stacked film layer and the d_{31} of ZnO film.

Figure 6 shows the calculated permeability agrees with measured values but the rate of change was only 0.35%. This is because the permeability in micro structure is degraded from 1500 to 447 and the silicon membrane was as thick as 15 μm. The rate of permeability change can be enhanced to 11% by removing the 15 μm thick silicon membrane and also by improving the permeability from 450 to 1500.

IV. ELECTROSTATIC TYPE DEVICE

Figure 7 shows the schematic view of the magnetoelastic-electrostatic type microdevice. The 0.5 μm thick FeSiB film was rf-sputter deposited onto a 50 μm thick soda glass substrate and 0.4 μm thick Au film for electrode was also deposited onto the opposite surface. This film-substrate was fixed over a grooved silicon wafer having a Au film electrode at the bottom of the groove. The groove is 40 μm deep and formed by the 10% TMAH anisotropic wet-etching process. With applying a voltage between the two Au electrodes, attractive electrostatic force is generated and the FeSiB film feels tensile stress. Therefore, the permeability always increases regardless of the polarity of the applied voltage.

The generated electrostatic force f operates as a uniformly distributed load, w, and is proportional to the square of the applied voltage V,

$$w = (f/l) = -(\varepsilon_0 b/2)(V/d)^2. \tag{3}$$

When ε_0 is the permittivity of vacuum, b the beam width and d the beam thickness. Let the beam length be l, then the deflection y of the beam is given as follows.

$$y = -(w/24EI)x^2(l-x)^2, \tag{4}$$

where I is the geometrical moment of inertia and x the distance from the end of the beam along length direction. Then the radius R of beam curvature is given as $I/R = d^2y/dx^2$. Substituting R into (1) and (2), we obtain the permeability change.

The observed permeability change was in phase as the applied ac voltage and it roughly agreed with theory as shown in Fig. 8. The observed permeability change was 0.23% when 2 Hz, ± 77.5 V ($\pm 0.7\times 10^6$ V/m) sinusoidal electric field was applied. The calculation above predicted that the permeability change can be improved to 80% if both the groove depth and the glass substrate are as thin as 20 μm, respectively.

Time domain observation of the initial permeability was done using a figure-8 coil and a two-phase lock-in amplifier. Figure 9 shows the ac component of the initial permeability when a 2 Hz sinusoidal electric field is applied. The permeability varied at double the frequency of applied field because the strain due to the static field was always unidirectional.

V. CONCLUSION

A magnetostrictive-piezoelectric type micro device has been microfabricated using sputter deposited FeSiB amorphous magnetostrictive film with soft magnetic property and the ZnO piezoelectric film. Micromagnetostrictive-electrostatic type is also possible using the FeSiB film. The feasibility of these devices has been clarified although the rate of obtained permeability change was less than 1%. These device characteristics could be improved to 11% for piezoelectric type and to 80% for electrostatic type by the optimization of device dimensions and reduction of process damage to the magnetic film.

[1] K. I. Arai, C. S. Muranaka, and M. Yamaguchi, IEEE Trans. Magn. **30**, 916 (1994).
[2] T. Honda, K. I. Arai, and M. Yamaguchi, J. Appl. Phys. **76**, 6994 (1994).
[3] E. Quandt and K. Seemann, *Proc. IEEE Micro Electro Mechanical Systems (MEMS 95)*, p. 273 (1995).
[4] M. Inoue, Y. Tuboi, N. Yokokawa, and T. Fujii, IEEE Trans. Magn. **26**, 1465 (1990).
[5] M. Naoe, H. Yamamoto, and S. Yamanaka, J. Appl. Phys. **50**, 7606 (1979).
[6] N. Chubachi, M. Minakata, and Y. Kikuchi, Jpn. J. Appl. Phys., Suppl. **2**, Pt. 1, 737 (1974).
[7] N. F. Foster, Proc. IEEE **53**, 1400 (1965).
[8] G. A. Rozgonyi and W. J. Ploito, Appl. Phys. Lett. **8**, 220 (1996).
[9] M. D. Mermelstein and A. Drandridge, Appl. Phys. Lett. **51**, 545 (1987).