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Research Report

Micromachined Thin Film Magnetoimpedance Element for Use in Integrated Magnetic Sensors

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ABSTRACT A micromachined magnetoimpedance (MI) element was prepared and its MI properties were researched. A SiN/Al/NiFe/SiO_2 film structure was formed on a (100)-oriented silicon wafer and fabricated by photolithography and etching. A $Ni_{80}Fe_{20}$ film with almost zero magnetostriction formed using bias magnetron sputtering under a magnetic field was adopted as a magnetic layer of the MI element, and magnetic anisotropy was induced parallel to the longitudinal direction of the element. Sensitivity according to the maximum fractional change in impedance increased with thickness and length, and reached the maximum value for a width of 20 μm. The values for which the MI element had the best performance were 38% for the sensitivity, 1446 ppm/°C for the temperature coefficient of impedance and 712 ppm/°C for the temperature coefficient of sensitivity. These values were much better than those of conventional magnetoresistance (MR) sensors. Therefore, these micromachined MI elements have a good performance for use in integrated magnetic sensors.

KEYWORDS Magnetoimpedance, Soft Magnetic Material, Permalloy, Micromachining, Thin Film, Impedance, Resistance, Reactance, Temperature, Permeability

1. Introduction

Recently, magnetic sensors(1-6) utilizing the magnetoimpedance (MI) effect in an amorphous wire and a soft magnetic film were proposed, and are expected to offer highly sensitive magnetic sensors for automotive uses such as rotation, angle, and position sensors. In order for these sensors to be used in automobiles, it would be helpful to miniaturize them and include them in a monolithic integrated circuit. However, magnetic sensors based on amorphous wires are unsuitable for use with a monolithic device, because these sensor elements are too large for integrated circuit processing. Furthermore, the MI properties of these sensors worsen after annealing above 400°C because they employ amorphous magnetic materials such as FeCoSiB. On the other hand, hall sensors(7) and magnetoresistance (MR) sensors(8) are typical integrated magnetic sensors produced by integrated circuit fabrication processes such as deposition, photolithography, etching, and annealing above 400°C. We propose a micromachined thin film MI sensor formed by an integrated circuit fabrication process, which includes annealing above 400°C.

The purpose of this research is to miniaturize a thin film MI sensor and to obtain a highly sensitive magnetic sensor in order to enable suitable integrated magnetic sensors for automotive use. In this paper, we describe a micromachined thin film MI element and its properties.

2. Experiment

2. 1 Preparation

Figure 1 shows the schematic view of a micromachined thin film MI element. A SiN/Al/NiFe/SiO_2 film structure was formed onto a (100)-oriented silicon wafer and processed by photolithography and etching. A 1-μm-thick thermally oxidized SiO_2 film was used as an insulating layer. The magnetic layer consisted of a $Ni_{80}Fe_{20}$ soft magnetic film with almost zero magnetostriction prepared by bias magnetron sputtering in a magnetic field and patterned by wet etching. Magnetic anisotropy was induced parallel or perpendicular to the driving current direction under an anisotropic field of 7 Oe. The magnetic layers ranged from 0.2 to 2 μm in thickness, 0.5 to 4 mm in length, and 5 to 400 μm in width. The pads consisted of an Al film prepared by magnetron sputtering and patterned by wet etching. The pads were 1 μm thick and 50000 μm^2 in area. The protective layer consisted of a 0.5-mm-thick SiN film prepared by plasma chemical vapor deposition and patterned by reactive ion etching. **Figure 2** shows a schematic view of a micromachined thin film MI element, which was annealed at 400 and 450°C after the deposition.

2. 2 Evaluation Method

The magnetoimpedance (MI) properties of the MI elements were measured using an impedance analyzer (4194A; Hewlett Packard, USA) in the frequency range from 10 to 100 MHz under a magnetic fields ranging from –100 to 100 Oe. The driving current was 9.5 mA. The temperature dependence of the MI properties was measured in a thermostatic oven at temperatures ranging from – 40 to 85°C.

3. Results

3. 1 Magnetoimpedance Properties of the MI Elements

Figure 3 shows the MI properties of an element in which magnetic anisotropy was induced perpendicular to the driving current direction. The impedance drastically changed as the magnetic field increased, reaching a maximum at a magnetic field of 7 Oe, which corresponded to the anisotropic field of the magnetic film. These profiles are similar to those for typical MI sensors.(1-6) The sensitivity, defined as the maximum fractional change in impedance $\Delta Z(=Z_{max}-Z_0)/Z_0$, was 112%.

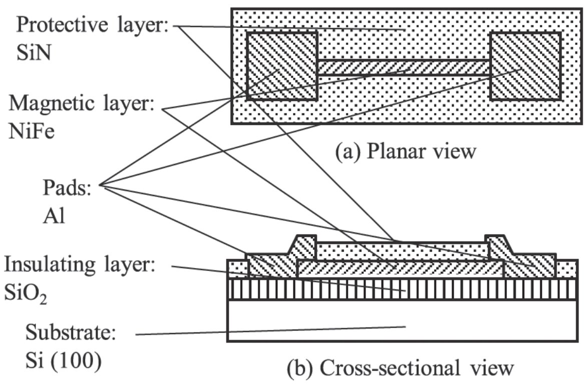

Fig. 1 Schematic drawing of micromachined thin film MI element.

Figure 4 shows the MI properties of an element in which magnetic anisotropy was induced parallel to the driving current direction. The impedance monotonically decreased with increasing magnetic field. These profiles are similar to those for typical magnetoresistance (MR) sensors.(8) Thus, the developed sensor is suitable for a wide range of magnetic field sensing applications, although its sensitivity is lower than that of conventional MI sensors. The sensitivity was 30% in this case, which is much higher than that for typical MR sensors,(8) despite the fact that it is miniaturized.

Figure 5 shows the dependence of the sensitivity on the annealing process. It can be seen that the sensitivity changed very little after annealing at 400 or 450°C, indicating that the micromachined MI element is suitable for integrated circuit fabrication processes.

d = 2 μm, L = 2 mm, W = 10 μm

Fig. 2 Photograph of micromachined thin film MI element.

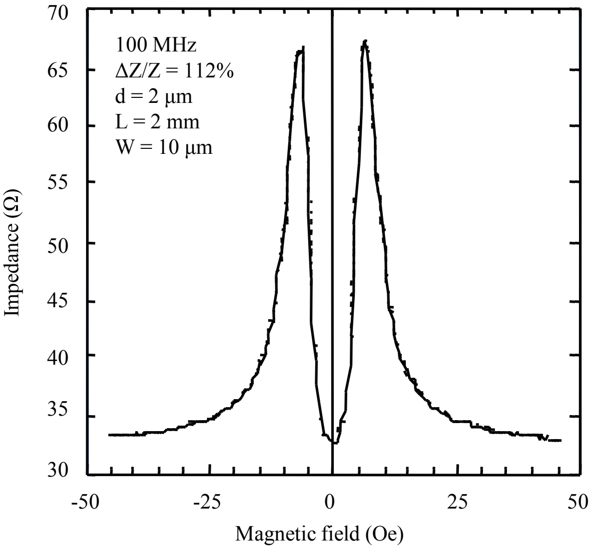

Fig. 3 Magnetoimpedance properties in NiFe MI element. (Magnetic anisotropy was induced perpendicular to the current direction.)

3. 2 Dependence of Sensitivity on Dimensions

Figures 6 and **7** show the dependence of the sensitivity on the magnetic layer thickness and the driving frequency for an MI element in which magnetic anisotropy was induced parallel to the driving current direction. The sensitivity increased monotonically with film thickness. It also increased with frequency, except for a film thickness of 2 μm.

These results can be explained as follows. In thin elements at low frequencies, the resistance is dominant, so the impedance induced by a magnetic field changes very little because the skin effect is extremely weak. On the other hand, in thick elements at high frequencies, the reactance is dominant, so the impedance depends on the permeability, which is determined by the magnetic field.(6) The reason that the sensitivity of the 2-μm-thick device had a maximum at a frequency of 40 MHz is probably that the permeability above 40 MHz decreased with eddy current losses in the magnetic film, while the reactance increased with frequency.

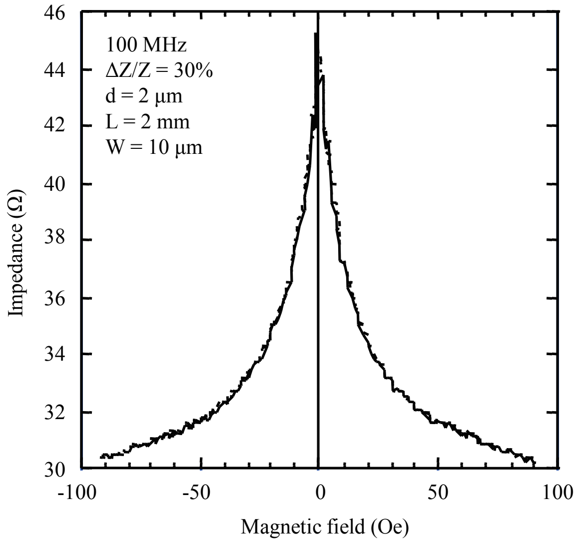

Fig. 4 Magnetoimpedance properties in NiFe MI element. (Magnetic anisotropy was induced parallel to the current direction.)

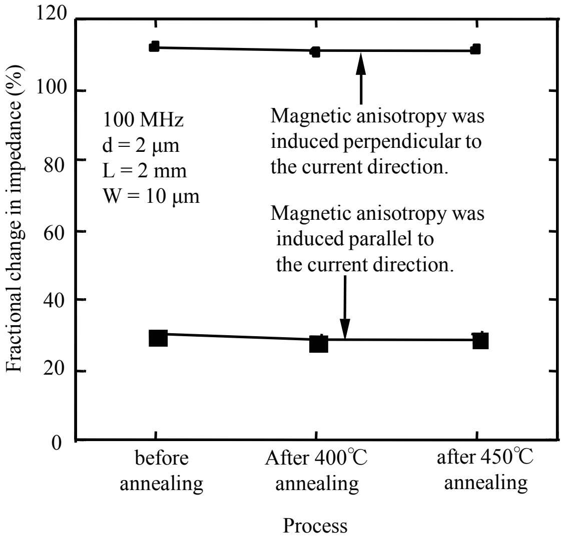

Fig. 5 Dependence of sensitivity on the process.

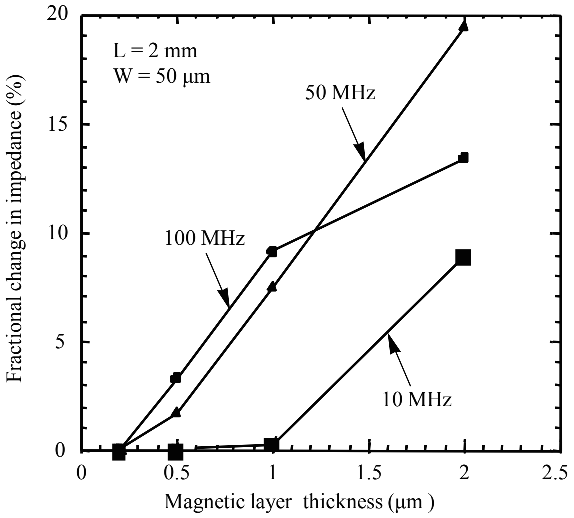

Fig. 6 Dependence of sensitivity on thickness of magnetic film.

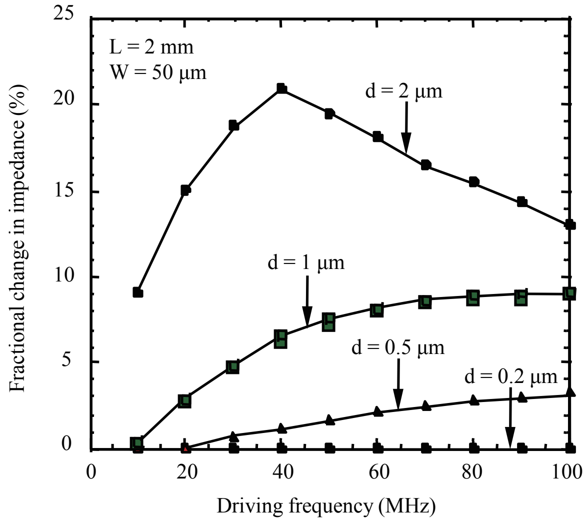

Fig. 7 Dependence of sensitivity on driving frequency.

Figures 8 and **9** show the dependence of the sensitivity on the length and width of an MI element in which magnetic anisotropy was induced parallel to the driving current direction. Although the sensitivity increased monotonically with length, it exhibited a maximum for a width of 20 μm.

These results can be explained by changes in permeability induced by changes in the magnetic field, since the impedance depends on the permeability of the magnetic film. The dependence of permeability on the dimensions of a magnetic thin film were calculated by Kikuchi et al.,(6) and the permeability induced by the magnetic field increased considerably with the increase in length and the decrease in thickness and width. The sensitivity was a maximum for a width of 20 μm because the reactance component of the impedance decreased with decreasing width while reactance increased with decreasing width.

3. 3 Temperature Properties of the MI Elements

Figure 10 shows the dependence of the impedance drift under zero magnetic field on temperature for an MI element in which magnetic anisotropy was induced parallel to the current direction. The impedance drift ΔZ is defined as the fractional change in impedance under zero magnetic field at temperature T.

$$\Delta Z = (Z_T - Z_{T=25°\mathrm{C}}) / Z_{T=25°\mathrm{C}} \qquad (1)$$

The temperature coefficient of impedance TCZ was calculated from the slope of the curves, and the results are shown in the figure.

$$TCZ = \Delta Z / \Delta T \qquad (2)$$

TCZ was 3301 ppm/°C at 10 MHz, which is almost the same as that for typical MR sensors.(8) TCZ decreased with increasing frequency, reaching 1446 ppm/°C at 100 MHz. This value is much lower than that for typical MR sensors.

Figure 11 shows the dependence of the temperature sensitivity of an MI element in which magnetic anisotropy was induced parallel to the current direction. The sensitivity drift $\Delta(\Delta Z(=Z_{max}-Z_0)/Z_0)$ is defined as the fractional change in sensitivity at temperature T.

$$\Delta(\Delta Z/Z)=\{(\Delta Z/Z)_T-(\Delta Z/Z)_{T=25°\mathrm{C}})\}/(\Delta Z/Z)_{T=25°\mathrm{C}} \qquad (3)$$

The temperature coefficient of sensitivity TCS was calculated from the slope of the curves, and the results are shown in the figure.

$$TCS = \Delta\,(\Delta Z/Z)/\Delta T \qquad (4)$$

TCS was –2432 ppm/°C at 10 MHz, which is almost the same as that for typical MR sensors.(8) TCZ changed from negative to positive with increasing frequency, reaching 712 ppm/°C at 100 MHz. This value is much lower than that for typical MR sensors.

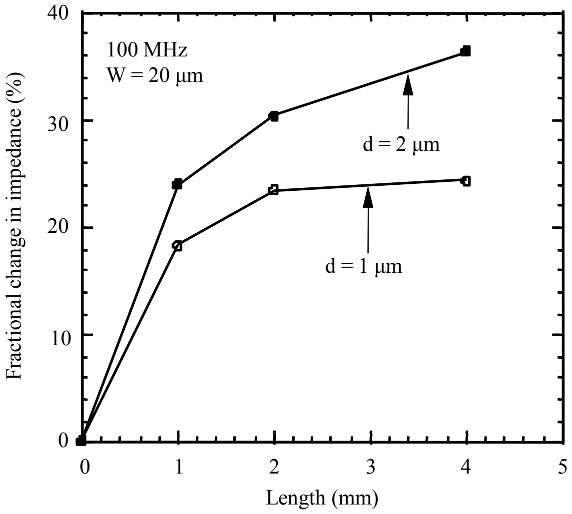

Fig. 8 Dependence of sensitivity on length.

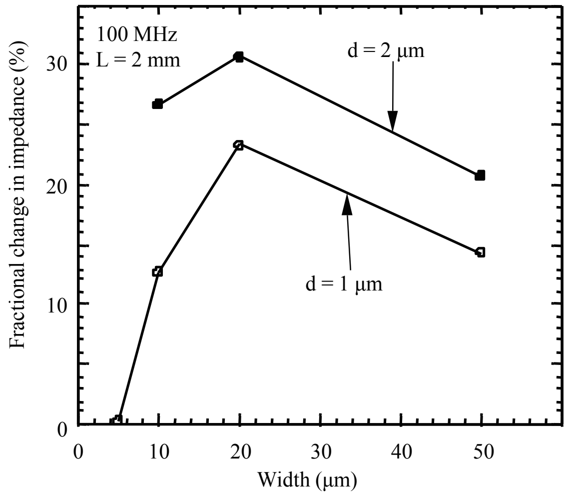

Fig. 9 Dependence of sensitivity on width.

4. Conclusion

We presented a micromachined thin film magnetoimpedance (MI) element consisting of a SiN/Al/NiFe/SiO_2 film and investigated its MI properties. The sensitivity, defined as the maximum fractional change in impedance, increased with thickness and length, with a maximum value at a width of 20 μm. The micromachined MI element with the best properties had a sensitivity of 38%, a temperature coefficient of impedance of 1446 ppm/°C, and a temperature coefficient of sensitivity of 712 ppm/°C at a driving frequency of 100 MHz. These values were much better than those for typical integrated magnetoresistance (MR) sensors. Therefore, these micromachined MI elements have great potential for use in highly sensitive integrated magnetic sensors.

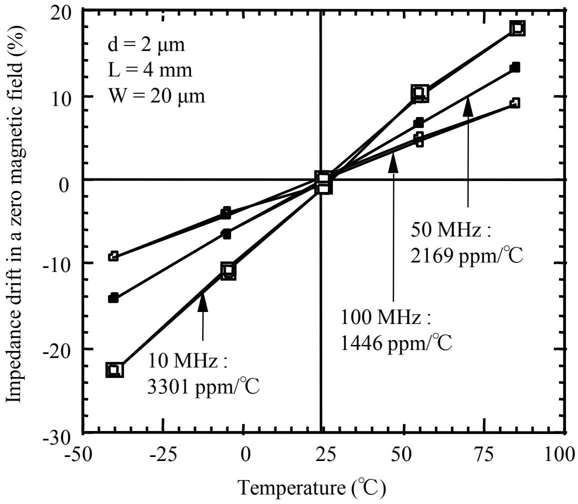

Fig. 10 Dependence of impedance drift in zero magnetic field on temperature.

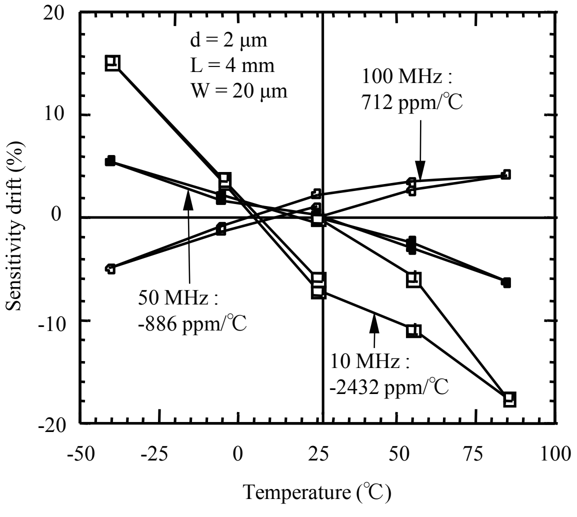

Fig. 11 Dependence of sensitivity on temperature.

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Figs. 1-11
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