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IMPEDANCE STRAIN GAUGE CHARACTERISTICS OF GLASS COVERED AMORPHOUS MAGNETIC WIRES

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Impedance strain gauge characteristics of amorphous wires prepared by glass-coated melt spinning method are reported. A change in wire impedance Z with a strain ε is enhanced by annealing after glass removal. The gauge factor S_e (= ΔZ/Z/ε) is estimated to be more than 2000 for the 21μm diameter Co-based $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ wires due to the skin effect. For the case of 17 μm diameter Co-based wires, a linear impedance change characteristics is observed in a wide range of strain (ε = ± 0.03%). Although Fe-based $Fe_{77.5}Si_{7.5}B_{15}$ 20 μm diameter wires have a high positive magnetostriction, S_e of Fe-based wires is not higher than that of the nearly zero magnetostrictive Co-based wires. The impedance gauge sensors based on $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ wires show both sensitive and linear response for the torque detection.

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1. Introduction

There are many devices employing strain gauges as the sensing element for measuring several physical quantities such as force, pressure, torque, acceleration and displacement. Semiconductor strain gauges have a large gauge factor S_e (=ΔR/R/ε) of 200 because of the piezoresistive effect. However, semiconductor gauges are quite sensitive to temperature variation [1].

Recently, a new gauge element using amorphous wires has been investigated [2,3]. The inverse magnetostrictive effect leads to a change of permeability in the wires so that applying stress can change the impedance of the amorphous wires due to the skin effect with high frequency current excitation[2]. As a result of stress dependence impedance change, the gauge factor of about 2000 has been obtained for CoSiB amorphous wires [3].

Impedance strain gauge characteristics of amorphous wires prepared by glass-coated melt spinning method are reported here. Amorphous glass-covered magnetic wires, which can be made in the very thin form, have excellent mechanical and electromagnetic properties[4]. Both very thin form and excellent mechanical properties are necessary for attachment of the wire gauge on the elastic element to produce a signal, which is related quantity to be measured. Excellent electromagnetic properties would contribute to the high signal to noise ratio for strain detection. A torque measuring system based on glass-covered $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ wires is presented for a typical application of the high sensitive impedance strain gauges.

2. Impedance-strain characteristics

Fig. 1 shows an experimental system to measure strain gauge characteristics of amorphous wires. Two conductor pads were glued on a surface of a metal plate. Both ends of the amorphous wire are bonded on the pads by soldering. All wires used in this investigation were kindly provided by Institute of Technical Physics, Iasi, Romania. When a bending moment M (= *Fx*) is applied to the plate, a strain is induced in the amorphous wires. In case of a deformation of a plate is sufficiently small, the induced strain is expressed as

$$\varepsilon = (h+H/2)\mathrm{M}/\mathrm{EI}, \quad (1)$$

where E is the Yong's modulus and I is an area moment of inertia. The value of impedance |Z| is evaluated from the equation $|Z| = V_w/I_w$, where V_w is an amplitude of the voltage e_w which appears between both ends of the wire, and I_w is an amplitude of current i_w which flows through into the amorphous wire.

Fig. 2 shows impedance Z versus strain ε characteristics of Co-based $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ amorphous wires after glass removal. A diameter Φ of the wire is 21 μm and a length l is 5 mm. The peak to peak value of applied current $I_{p\text{-}p}$ is 5 mA and frequency is 5MHz. The large impedance change, which is due to the skin effect, was obtained by annealing with a dc current of 50 mA for 20 minutes flowing through the wires. The linear increment of the impedance is observed from ε = - 0.01% to ε = 0.01%. The gauge factor S_e (= $\Delta Z/Z/\varepsilon$) is estimated to be more than 2000 in this linear region. The value of S_e is more than twice larger than that of CoSiB at 5 MHz[2]. When the strong skin effect is induced by the high frequency i_w, the wire impedance Z is expressed as

$$|Z| = \frac{a}{2\sqrt{\rho}} R_{dc}\sqrt{\omega\mu_\theta(\sigma)} \quad (2)$$

where a is a radius of the wire, ρ is a resistivity, $R_{dc}$is a dc resistance, ω is an angular frequency, μ_θ is a circumferential permeability, and σ is applied stress to the wire. According to eq.(2), a change in μ_θ with σ due to the inverse-magnetostriction effect leads to an impedance change.

Carrying the ac current i_w, changes in circumferential BH loops with a strain were measured. Fig. 3 shows $B_\theta H_\theta$ loops for annealed Co-based wires. H_θ is a circumferential magnetic field of $i_w/2\pi a$.

B_θ is obtained from the relation $e_L = d\phi_\theta/dt$, where ϕ_θ is a circumferencital flux and $\boldsymbol{e}_L$ is an inductive component of e_w[5]. The coercivity H_c depends on the strain, which makes internal stress to the wire.The coercivity decreases with applying a positive strain, while that increases with applying a negative strain. Generally μ increases with decreasing H_c. The change in H_c seems to be reflected on the change of the impedance of the wires due to the skin effect.

Fig. 4 illustrates impedance versus strain ε characteristics of 17 μm diameter wires ($Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$) after glass removal. S_e is estimated to be about 300 for annealed samples. The linear impedance change in a wide range of strain ($\varepsilon = \pm$ 0.03%) was obtained by annealing with a dc current of 40mA for 20 minutes. A linear response is preferable for an accurate measurement of a strain.

The impedance-strain characteristics of high magnetostrictive $Fe_{77.5}Si_{7.5}B_{15}$ wires (λ_s = 35 x 10^{-6} for as-cast[4]) are also investigated to compare with the properties of the low magnetostrictive $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ wires (λ_s = -1 x 10^{-7} for as-cast[4]).

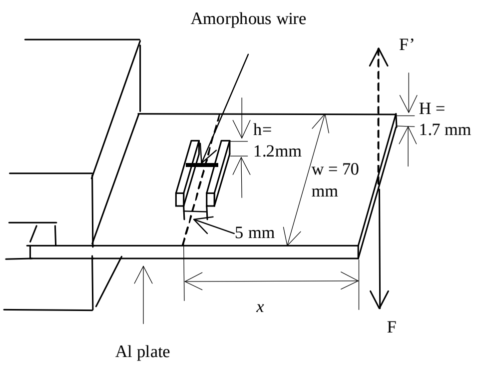

Fig. 1 Experimental system for impedance gauge characteristics.

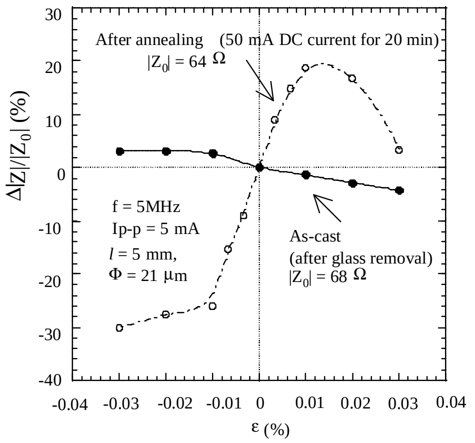

Fig.2. Z vs. ε characteristics for Co-based 21 μm wires.

Fig. 5 shows Z versus ε characteristics of Fe-based $Fe_{77.5}Si_{7.5}B_{15}$ wires. A slight enhancement of an impedance change was obtained after annealed with a tension of 160 MPa and a dc current of 50 mA. S_e of the Fe-based wires is not higher than that of 21 μm diameter Co-based wires.

Fig. 6 illustrates $B_\theta H_\theta$ characteristics of the tension-annealed $Fe_{77.5}Si_{7.5}B_{15}$ wire. Both a slope of $B_\theta H_\theta$ curve and the coercivity H_c show dependence on strain. The slope increases remarkably with applying a negative strain (ε = -0.02 %) due to a high positive magnetostriction, while an increase of H_c occurs at the same time. The increase of the slope leads to an increase in μ but the increase of H_c leads to a decrease in μ. As a result of the compensation effect, a change in μ seems to be suppressed.

3. Torque measurement

Fig. 7(a) shows a torque measurement system employing the impedance strain gauge sensor, which is based on the 17μm diameter $Co_{68.25}Fe_{4.5}Si_{12.25}B_{15}$ wire. A brass shaft with diameter of 13 mm was used for this experiment. In case of a torque T is applied to a metal shaft, the main direction of a stress is an angle of ±45 degree with shaft axis. Both ends of the amorphous wire are bonded on conductor pads glued on the shaft, aligning the wire axis in the direction of 45 degree. The maximum strain in that direction is expressed equation (3) [6].

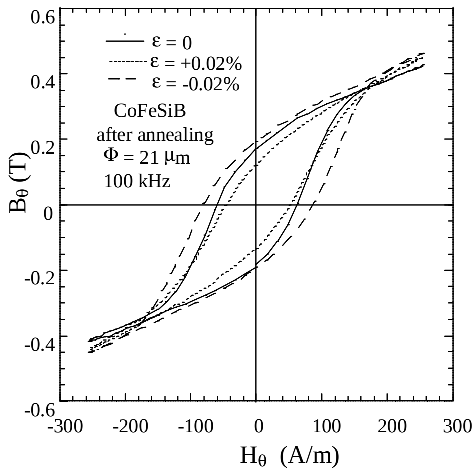

Fig.3. Change in $B_\theta H_\theta$ loops with a strain for Co-based wires.

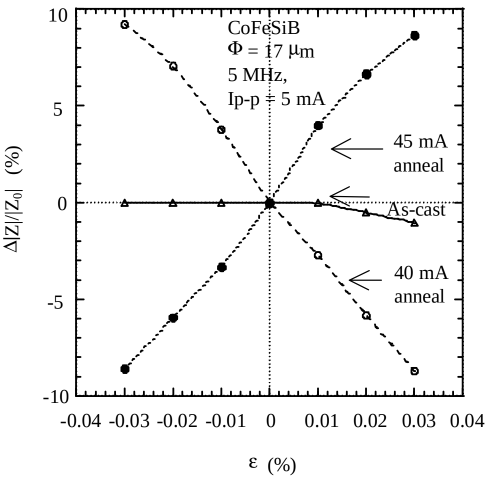

Fig. 4. Z vs. ε characteristics for Co-based 17 μm wires.

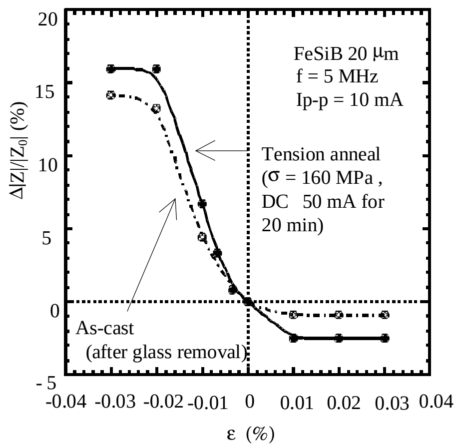

Fig. 5. Z vs. ε characteristics for Fe-based 20 μm wires.

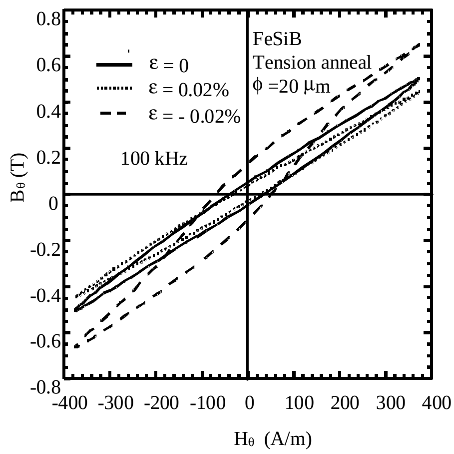

Fig. 6. $B_\theta H_\theta$ loops for Fe-based wires.

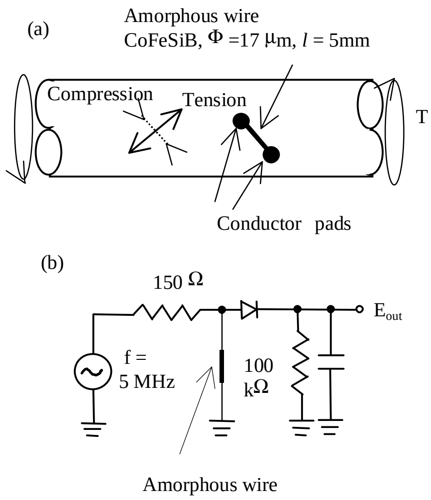

Fig. 7. Torque measuring system.

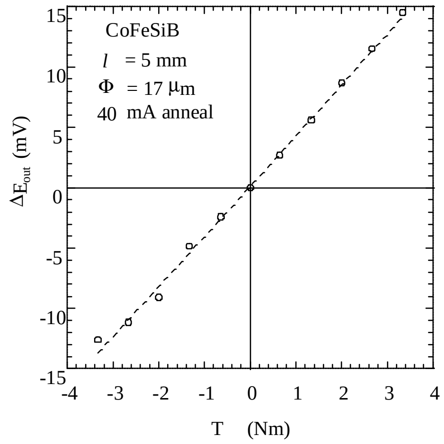

Fig. 8. Typical output characteristics of the impedance gauge sensor for torque detection.

$$|\varepsilon_m| = 16T(1+\nu)/(\pi E D^3), \tag{3}$$

where ν is the Poison ratio and D is a diameter of the shaft. The ac voltage source was used to apply the high frequency current to the amorphous wires. The ac voltage e_w is converted to a dc output voltage E_{out} by use of a peak hold circuit.

Fig. 8 shows the response of impedance gauge sensor for the torque detection. $\Delta E_{out} = (E_{out}(T) - E_{out}(T{=}0))$ is a differential voltage when no torque applied. A linear response was obtained in the range of ± 3 Nm, which corresponds to strain range of ± 0.01% in the wire.

For the case of power steering applications in the automotive industry, a torque sensor having a full scale of ± 10 Nm is expected [7]. Assuming 13 mm diameter steel shaft, the corresponding strain range is ± 0.015% for the full scale. Based on the experimental results presented here, impedance wire gauge sensors would have enough sensitivity and an excellent linearity to detect the steering torque. It will be necessary in future work to investigate a stability of the impedance gauge sensors. Developing of a brush-less torque sensor system would be necessary for a rotary shaft.

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