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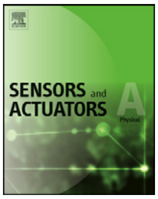

Piezoimpedane and pressure sensors with NiZn ferrite device

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ABSTRACT

The hydrostatic pressure effect on the magnetism, capacitance and impedance of a NiZn ferrite device has been investigated. Giant piezomagnetism, piezocapacitance and piezoimpedane independent on skin effect have been observed simultaneously under a pressure of several MPa. With increasing the frequency of the current applied across the ferrite device, the piezoimpedane has been found to undergo a maximum at a current frequency of 500 Hz. Under a pressure of 6 MPa, the maximum of piezoimpedane can reach about 71%. And the pressure sensitivity of the impedance can be higher than 0.18 MPa^{-1} when the pressure is lower than 3 MPa. Analysis shows that these giant pressure effects in the ferrite device result from the variation of the inner stress in the ferrite under an external pressure.

1. Introduction

When a magnetic material carrying an alternating current is subjected to an external magnetic field along the direction of the current flow, it exhibits a sharp change in its electrical impedance. This effect is known as the giant magnetoimpedance (GMI) effect [1]. The GMI effect is believed to stem from the skin effect, which results from the external field-induced change in the effective permeability (μ_{eff}) of the magnetic material [2]. On the other hand, it is well known that the permeability can also be changed by applying a stress on the magnet. Therefore, one can expect a behavior of external stress-induced change of the impedance in the GMI material. It is known as the giant stress impedance (GSI) effect [3,4]. GMI effect and the related GSI in Co-based or Fe-based amorphous ribbons or films and nanocrystalline materials have been extensively studied [5–8] and applied in fabricating highly sensitive magnetic sensors in last 10 years [9–11].

For the GSI effect mentioned above, a higher frequency alternating current is required since it depends on skin effect. The typical frequency needed for the GSI is no lower than 100 kHz. Additionally, a tensile stress is needed since the GSI occurs only in some wires or ribbons so far.

Recently, with a hydrostatic pressure and an ac current at a lower frequency than that in the case of the GSI in amorphous ribbons, we have observed another kind of GSI effect that is independent on skin effect in a magnetic device. It is, in fact, a giant piezoimpedance (GPI) effect. Pressure effect on magnetic cores has ever been investigated about 10 years ago [12], but further studies on the related piezoimpedance and other pressure effect based on the piezomagnetism have seldom seen so far. In this work, a systematic investigation of the GPI effect and other related pressure effect in ferrite device is presented. We will show that the sensitivity of the GPI effect can reach 18.4% MPa^{-1} in a sensitive area of pressure.

2. Piezoimpedance depending on piezomagnetic effects

It is well known that most magnetic materials, especially some ferrites, can show a piezomagnetic effect. For a magnet with very high permeability μ, the magnetization mainly depends on the movement of the wall of magnetic domain. For such a magnet, the initial permeability in the process of reversible magnetization under an external stress is given by

$$\mu_{\text{i}} = \frac{2\mu_0 M_{\text{s}}^2 l}{3\pi^2 \delta \lambda_{\text{s}} \sigma} + 1, \tag{1}$$

where M_{s} is the saturated magnetization, λ_{s} the saturated magnetostrictive coefficient, l and δ are the width and thickness of the

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wall of magnetic domains, respectively, and σ is the internal stress, which can be changed by external stress. Thus piezomagnetic effect in the reversible process for a magnet with a high permeability can be expressed as

$$\frac{\Delta\mu_{\mathrm{i}}}{\mu_{\mathrm{i}}}=-\frac{\mu_{\mathrm{i}}-1}{\mu_{\mathrm{i}}}\frac{\Delta\sigma}{\sigma}\approx-\frac{\Delta\sigma}{\sigma}. \tag{2}$$

Eq. (2) suggests that the piezomagnetic effect can be enhanced with increasing μ and $\Delta\sigma$, but is inverse proportional to practical internal stress σ. For this reason, if a search coil is circled on such a magnet, one can expect to observe the piezomagnetic effect, which is presents a stress-induced change of inductance L in the coil taking the relation $L = VN^2\mu_0\mu$ into account, where n (the circles in a unit length of the coil), V (the volume surrounded by the coil) and μ_0 (permeability in vacuum) are all constants for a given coil [13]. In other words, the piezomagnetic effect can also be written as

$$\frac{\Delta\mu_{\mathrm{i}}}{\mu_{\mathrm{i}}}=\frac{\Delta L}{L_0}, \tag{3}$$

where L_0 is the inductance of the coil without pressure. Besides the inductance, a coil always has a resistance and a distributed capacitance [14]. When an ac current is applied across a coil, the measurable values of those parameters will be related one after another and related to the current frequency $\omega/2\pi$ closely. Generally, the equivalent circuit of an inductor suggests that the inductance and capacitance of an inductor should be parallel, and they are serial with its resistance, as shown in Fig. 1 [15]. In this model, the effective capacitance C_{s} and the impedance Z of the inductor can be, respectively, expressed as

$$C_{\mathrm{s}}=C_{\mathrm{p}}-\frac{L}{R_{\mathrm{p}}^2(1-\omega^2C_{\mathrm{p}}L)}, \tag{4}$$

$$Z=\frac{\omega LR_{\mathrm{p}}}{\sqrt{\omega^2L^2+R_{\mathrm{p}}^2(1-\omega^2C_{\mathrm{p}}L)}}, \tag{5}$$

where R_{p} is the resistance of the inductor under a dc current, C_{p} is the capacitance independent on current frequency. C_{p} can usually be extrapolated from the measured C_{s} versus frequency without external magnetic field or stress.

On the other hand, it is known that, when in an alternative electromagnetic field, the magnetic relaxation of a magnet can lead to permeability dispersion, $\tilde{\mu}=\mu'-i\mu''$, where μ' and μ'' are elastic and viscous permeability, respectively. Thus, the effective permeability should be

$$\mu_{\mathrm{eff}}=\sqrt{\mu'^2+\mu''^2}=\sqrt{\frac{\mu_{\mathrm{i}}^2+(\omega/\omega_{\mathrm{c}})^2}{1+(\omega/\omega_{\mathrm{c}})^2}}, \tag{6}$$

where ω_{c} is the frequency of relaxation. Eq. (6) indicates that the permeability in an alternative field is also a function of the field frequency. Considering the relation $L = VN^2\mu_0\mu_{\mathrm{eff}}$ and Eqs. (4) and (5), one can expect to observe the effects of piezomagnetism (PM), piezocapacitance (PC) and piezoimpedance (PI) in a coil with magnetic core simultaneously. Collecting results from Eqs. (3)–(6), the PM, PC and PI are, respectively, given by

$$\frac{\Delta L}{L_0}=-\frac{\Delta\sigma}{\sigma}, \tag{7}$$

$$\frac{\Delta C_{\mathrm{s}}}{C_0}=\frac{L}{C_0R_{\mathrm{p}}^2(1-\omega^2C_{\mathrm{p}}L)^2}\frac{\Delta\sigma}{\sigma}, \tag{8}$$

$$\frac{\Delta Z}{Z_0}=\frac{-\omega LR_{\mathrm{p}}^3(1-\omega^2C_{\mathrm{p}}L)}{Z_0\left[\omega^2L^2-R_{\mathrm{p}}^2(1-\omega^2C_{\mathrm{p}}L)^2\right]^{3/2}}\frac{\Delta\sigma}{\sigma}, \tag{9}$$

where C_0 and Z_0 are the capacity and impedance without pressure. Eqs. (7)–(9) suggest that, with increasing external stress, the distribute capacitance increases, but the inductance and impedance decrease.

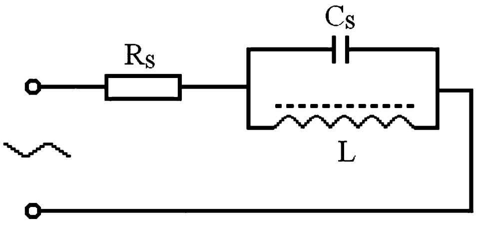

Fig. 1. Equivalent circuit of the ferrite device.

3. Characterization of the pressure sensor with the ferrite device

Generally speaking, any one of ferromagnetic materials has the PM behavior. However, to get a sharp and repeatable PM effect, one should obtain a soft magnet with higher permeability. In this sense, NiZn and MnZn ferrites are some desirable magnets [16]. But NiZn was believed to work at higher frequencies. Commercial NiZn ferrite with nominal initial permeability at about 1000 was employed in this study. The geometrical shape of the magnetic core is also important for strong piezomagnetic effects. Magnets with closed magnetic circuit geometry are preferable. The ferrite cores used are in the shape of rings of 4 mm in height and 9 mm in diameter. A search coil of ten turns was wound and cemented with glue on to the ring. The present number of turns is not the optimal in the sensitivity, but it was found that the value measured on the turns is more stable.

A cylinder containing a piston was applied as a pressure container. The inner diameter of the cylinder is five times larger than that of the ring. The ring-shaped ferrite with the search coil was placed at the center of the container filled with powder of SiO_2, as shown in Fig. 2. The average grain size of the SiO_2 powder is about 1.5–2 μm. Thus, a pseudo hydrostatic pressure can be applied on the ferrite ring by applying a force on the piston. By the way, since there is not a strong electric field in the present pressure experiments, the dielectricity of SiO_2 powder can be ignored.

4. Experimental results and discussion

An ac electric bridge has been applied to measure the inductance L and capacitance C of the device. A function generator and a voltmeter were used to measure the impedance Z of it. In the measurement of the impedance, the search coil, the function generator

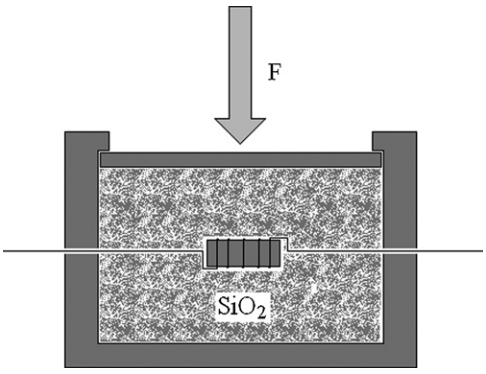

Fig. 2. Schematic draft of the pressure sensor with the ferrite device.