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Enhancement of impedance change at low frequency in a thin-film magnetoimpedance element

ABSTRACT

In this paper, we found an atypical profile on the frequency dependence of a thin-film magnetoimpedance element having a narrow width and a thickness of several microns in the lower frequency region, although a typical magnetoimpedance shows a single peak above the 100 MHz region. The observed peak achieves higher intensity and frequency with increasing applied bias DC magnetic field, and disappears at the higher applied field. Since the sensitivity of the element for the applied magnetic field maintains nearly the same level as that in the high frequency region, the existence of the peak in the low frequency region brings us a possibility to realize a thin-film magnetic field sensor with higher sensitivity operating in the low frequency region. We confirmed experimentally that the enhancement of impedance change in low frequency is attributed to a large permeability change in the low frequency region, which may contribute to the domain wall resonance.

1. Introduction

Giant magnetoimpedance (GMI) sensors have a high sensitivity and are typically influenced by the skin effect and changes in permeability when the sensor is applied to a magnetic field [1,2]. Such sensors, which are composed of amorphous wires, are currently used as compasses in mobile phones [3], and research aimed at developing biological [4–6] and medical [7,8] applications and nondestructive testing methods [9] for GMI sensors continues to advance. There are many efforts to investigate materials, sensor structures, controlling anisotropy and developing theoretical models for optimizing GMI elements to gain higher sensitivity, especially on wires and ribbons [10–14], and these works are well reviewed in Ref. [15]. These sensors using wires and ribbons generally have a thickness of dozens microns and operate below a frequency range of dozen megahertz [15].

A further advantage of using these sensors is the compatibility of thin-film GMI elements with miniaturized integrated electronic devices (driving and detecting circuits). Therefore, we studied the basic characteristics of thin-film GMI elements such as the incident power dependence [16], the effect of demagnetizing factor [17], and the effect of anisotropy direction [18], etc., and obtained the qualifications to achieve higher sensitivity. However, thin-film GMI elements with a thickness of several microns operate above 100 MHz; this is unsuitable for driving and detecting circuits, which normally operate below dozen megahertz.

In wires and ribbons, the permeability change is mainly contributed by domain wall motion when a bias field is applied and the skin effect becomes remarkable in the low megahertz region due to relatively large thickness. Therefore, the frequency profile of the impedance has ordinarily a single peak between several megahertz and dozens megahertz. On the contrary, domain wall motions are damped and the skin effect becomes significant above hundreds megahertz on a thin-film element. Thus, the frequency profile of the impedance for thin-film element shows a single peak attributed to ferromagnetic resonance in the several hundred megahertz region.

During our investigations about thin-film GMI elements, we found an atypical behavior on an element having a relatively narrower width and at the relatively low frequency with a thickness of several microns; the frequency profile of the impedance shows double peak depending on the applied bias field (another peak appears at lower frequency region). We consider that the observed phenomenon can be applied for developing a highly sensitive sensor operated at frequencies around the dozen megahertz region. Therefore, in this study, we investigated the exceptional impedance behavior in this regime using narrow thin-film GMI elements with a thickness of several microns and also discussed the novel impedance behaviors.

2. Experimental procedure

The magnetoimpedance elements composed of an amorphous $Co_{85}Nb_{12}Zr_3$ thin film were 20, 40, or 80 μm wide, 3 mm long, and 2 μm thick, and had an easy axis parallel to the width of the element. The thin films were deposited through magnetron sputtering and fabricated by photolithography. To control the easy axis direction of the elements, the elements were annealed at 673 K in vacuum and a static magnetic field of 240 kA/m (3 kOe) was applied parallel in the direction of the width of the element during annealing. The induced anisotropy field of the films was 640 A/m (8 Oe) and the coercivity was less than 8 A/m. Then, a 2-μm-thick Cu electrode was deposited. We measured the impedance of the elements using a network analyzer (HP8752A) and a wafer probe (Picoprobe 40A-GSG-150-LP) by applying AC current. The frequency of the AC current was alternated from 1 MHz to 1000 MHz and the incident power was −20 dBm. Thus, the elements were

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magnetized by the small AC magnetic field parallel to the width of the elements. Because the amplitude of the AC field was so small, the elements possess linear characteristics. A DC magnetic field was applied to the elements along the longitudinal direction using a Helmholtz coil. The section of the element in the center position (1 mm long) was used to avoid the deterioration of the sensor properties due to the demagnetizing field distribution at the edges [17]. We also observed the domain structure of the elements using a Kerr-effect microscope to consider the mechanism of the atypical behavior of impedance change observed during low frequency.

3. Experimental results

Fig. 1(a) shows the frequency dependence of the impedance of the elements for the applied different DC magnetic fields. In the case of a 80-μm-wide element (See Fig. 1(a)), the impedance is constant up to 100 MHz, and then increases slightly as the frequency increases when the applied field is zero, while the impedance profile shows a single peak above 500 MHz when the field is applied from 0.5 to 1.2 kA/m (6.5–15.1 Oe). When the DC field is applied to the element, the increase in impedance at the high frequency region is enhanced, as a result of which the skin effect becomes apparent owing to the increment of the permeability. The drop in the impedance above 500 MHz is attributed to ferromagnetic resonance. Though, in general, the impedance increases with increasing frequency and peaks for the region above 100 MHz due to ferromagnetic resonance on thin-film GMI elements, as shown in Fig. 1(a), a local maximum appears at 10 MHz for the applied field of 550 A/m (6.9 Oe) in the case of a 20-μm-wide element (See Fig. 1(c), the red arrow indicates the peak). Similar behavior was observed in the case of a 40-μm-wide element (See Fig. 1(b), around 15 MHz at 516 A/m). Fig. 1(d) represents the frequency dependence of the impedance of the elements for the 20-μm-wide element when the DC field was applied around 550 A/m (6.9 Oe) changing fields with smaller steps than Fig. 1(c). The peak height increases and the peak position shifts to a higher frequency with the increasing applied field (See the arrows in the figure).

Fig. 2 shows the impedance change plotted against the applied DC field when the frequencies changed from 10 to 100 MHz, for the 80- and 20-μm-wide elements. The profile for the 80-μm-wide element (Fig. 2(a)) shows a peak at approximately 640 A/m (8 Oe) with the frequency independence, while the peak value decreases with the decreasing frequency. This impedance behavior is explained as follows: based on a bias susceptibility theory [19,20], a magnetic moment of the element aligns with the direction of the applied DC field when the field achieves an anisotropy field and the permeability becomes maximum; therefore, inductance of the film also becomes maximum. With increasing frequency, the skin effect becomes predominant, which causes the increase in resistance of the element. Since the skin depth is also dependent on the permeability, the resistance has a peak at the anisotropy field [21]. In the case of the 20-μm-wide element, the change at low frequency is small compared with that at 100 MHz, but the ratio of impedance decrease is small compared with that of the 80-μm-wide element, while the sensitivity dZ/dH is almost the same: 14.1 Ω/Oe for 20 MHz and 16.1 Ω/Oe for 100 MHz. The sensitivity is defined as the maximum slope of the impedance profile against the applied field. The field intensity where the impedance shows a peak shifts to a higher field with increasing applied DC field.

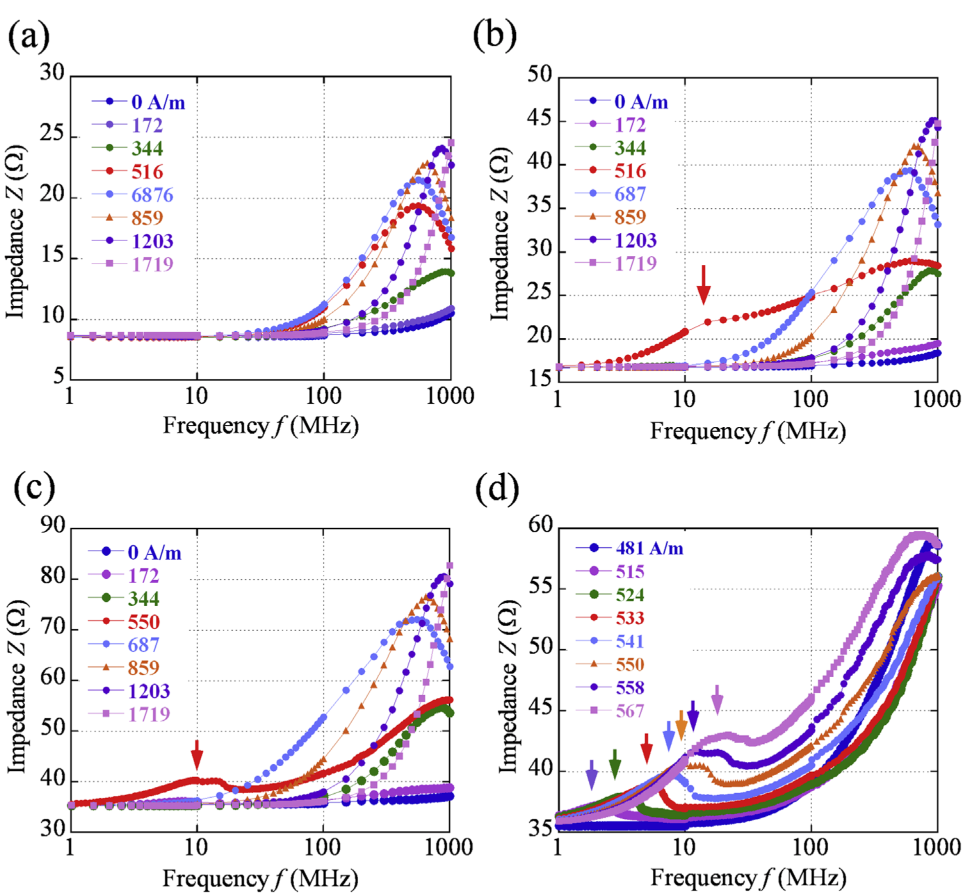

Fig. 1. Frequency dependence of the impedance of the elements for the applied different DC magnetic fields. Applied field changed from 0 to 1.7 kA/m. (a) 80-μm-wide element. (b) 40-μm-wide element. (c) 20-μm-wide element. (d) 20-μm-wide element with small applied field steps around 0.5 kA/m.