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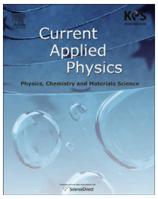

Low-field microwave absorption behaviors on single layer magnetic film and exchange coupled multilayer magnetic film

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ABSTRACT

This study examined the magnetization reversal effects on low-field microwave absorption in a $Fe_{91.6}B_{2.5}N_{5.9}$ single layered film with in-plane uniaxial magnetic anisotropy and a multi-layered film with giant magnetoresistivity using ferromagnetic resonance measurements at 9.84 GHz. Two different kinds of absorption modes were observed at near zero dc field and high dc field. The signals at high-field showed all the features of ferromagnetic resonance due to spin precession. However, the absorption signals at low-field should be associated with the switching field at unsaturated magnetic field region.

1. Introduction

Microwave absorption in nanostructured magnetic materials can be used to characterize physical parameters such as effective magnetization, effective magnetic anisotropy, damping constant, spin splitting *g* factor, high-frequency loss, and magnetic inhomogeneity [1]. In ferromagnetic materials, two types of microwave power absorptions can be obtained; ferromagnetic resonance (FMR) due to the spin dynamics at the saturated field region and low-field microwave absorption (LFMA) at the near zero magnetic field region. Conventional FMR signals can be observed due the absorption of a small transverse microwave field when the microwave frequency coincides with the frequency of magnetic spin precession. LFMA occurs at around a zero magnetic field via low-field magnetization processes [2]. LFMA has been observed in various materials including ferromagnetic materials such as high temperature superconductors, amorphous ribbons, glass coated microwires, ferrite nanoparticles, magnetic thin film with giant magnetoresistance (GMR), and magnetic nanowires [1–17]. LFMA in high temperature superconductors has been obtained as a signature for the transition to a superconductive state and multiphase [3–5]. For amorphous ribbons, the relationship between the magnetoimpedance (MI) and LFMA can be understood as the absorption of electromagnetic radiation by spin systems that are modified by a domain configuration and are strongly dependent on the anisotropy field [2,6]. The H. Chiriac group and H. Montiel group confirmed the magnetization process and magnetic anisotropy field as the presence or absence of glass in glass coated microwires [7–9]. For ferrites, the obtained absorption signal behaviors are similar to giant magnetoimpedance (GMI) [10–12]. In GMR films, the LFMA is correlated with magnetization reversal [13]. Recently, Joaquín et al. reported that LFMA signals in magnetic nanowires reflect the non-saturated remanent state [14,15]. For FeSi and Co thin film, absorption signals can be associated with non-resonant spin rotation in a partially saturated sample that results from the magnetization process of the ordered phase [16–18]. In this study, to verify the magnetization reversal process based on microwave absorption, FMR and LFMA signals were evaluated for the single layer magnetic film and exchange coupled magnetic film.

2. Experimental

To evaluate the magnetization process using LFMA signals, two types of representative thin films, a 500 nm-thick $Fe_{91.6}B_{2.5}N_{5.9}$ nanocrystalline thin film and an exchange coupled GMR film (Ta 5 nm/FeMn 8 nm/NiFe 8 nm/CoFe 2 nm/Cu 2 nm/CoFe 2 nm/NiFe 8 nm/Ta 5 nm/Si substrate) were prepared by RF and DC magnetron sputtering. The magnetic properties of these films were measured

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using a vibrating sample magnetometer (VSM) and electron spin resonance (ESR) spectrometer. The ESR spectrometer is a bipolar home-made X-band (9.84 GHz) with a TE_{101} resonant cavity and a modulation frequency of 100 kHz.

3. Results and discussion

In a $Fe_{91.6}B_{2.5}N_{5.9}$ film, the saturation magnetization ($4\pi M_s$) and coercivity (H_c) at the hard direction were 9.5 kG and 0.4 Oe, respectively. The in-plane uniaxial magnetic anisotropy field (H_k) was 5 Oe, as shown in Fig. 2(b). To confirm the magnetic properties and magnetization process, the FMR and LFMA of this film for two opposite directions of the field sweep were presented in Fig. 1. These absorption signals were observed under the condition that magnetic field was applied to the in-plane hard axis (HA) or easy axis (EA) on the direction of the film and a microwave field (h_{rf}) applied to the out-of plane of the film. The derivative of microwave absorptions revealed two different signals. Strong absorption peaks were observed over ±500 Oe of the applied magnetic field (H_{app}). These peaks should be associated with ferromagnetic resonance, satisfying the Larmor relationship. The other absorption peaks (LFMA mode) were observed at around a zero magnetic field. In general, the FMR resonant frequency relation with an applied magnetic field can be obtained from the FMR conditions which are expressed as Eqs. (1) and (2). The FMR absorptions are due to absorption in the full saturation state. The FMR conditions for the film in-plane uniaxial geometry are written as follows: [19–21]

$$\frac{\omega}{\gamma} = \sqrt{(H_{res}+H_k)(H_{res}+H_k+4\pi M_s)}, \qquad (1)$$

$$H_{res} = (H_e+H_h)/2,\ \ H_k = (H_h-H_e)/2, \qquad (2)$$

where ω is the microwave angular frequency, H_{res} the resonance magnetic field, H_k the in-plane uniaxial anisotropy field, γ ($=ge/2mc$, where g, e, m, and c are the spin splitting g factor, electron charge, electron mass, and speed of light, respectively) a gyromagnetic splitting factor, H_e and H_h are the resonance magnetic field along the easy and hard axis of the film, respectively.

The resonance magnetic fields for the major and minor peaks found at 543 Oe, and 604 Oe, respectively. The shape of the resonance peaks had asymmetry, which was attributed to the magnetic inhomogeneity. The FMR signals showed additional small minor modes around the major absorption modes, in which the minor modes could represent the magnetic inhomogeneity possibly due to the existence of meta-stable mixed phases, such as γ'-Fe_4N phases in this film [22]. This different magnetic phase appeared in the FMR signals with an asymmetrically broad peak. The obtained g factor was 2.16. The uniaxial magnetic anisotropy fields could be obtained by M–H hysteresis curves and FMR peaks. The uniaxial magnetic anisotropy fields by the FMR absorption peaks coincide with those of the VSM results, with a value of approximately 5 Oe. In addition, the uniaxial magnetic anisotropy fields could be deduced by the switching field (H_{sw}) on low-field microwave absorption signals. At zero magnetic field, the microwave absorption by the spins was strongly damped because they had a random distribution. As the magnetic field increased, the domains aligned closer to the field direction grew at the expense of the domains aligned to the different direction. Some microwave absorption could take place due to this unbalanced domain structure. When the magnetic field reached the anisotropy field value, spin rotation goes through a maximum because the magnetic field finally overcomes the anisotropy [3]. Fig. 2(a) and (c) shows the derivative microwave absorption in the oblique field compared to those of M–H curves (Fig. 2(b)) at the easy and hard direction of the film. The H_{sw} values for EA and HA on LFMAs were approximately 3.4 Oe and 6 Oe, respectively, in which the H_{sw} at HA was almost coincident with the magnetic anisotropy field from the VSM and FMR results. Secondary LFMA signals at EA and HA were observed at approximately 13 Oe. This suggests that the initial stage of the single domain direction was almost in the same direction with the applied magnetic field. Overall, the LFMA results show the magnetization processes at the unsaturation state in detail.

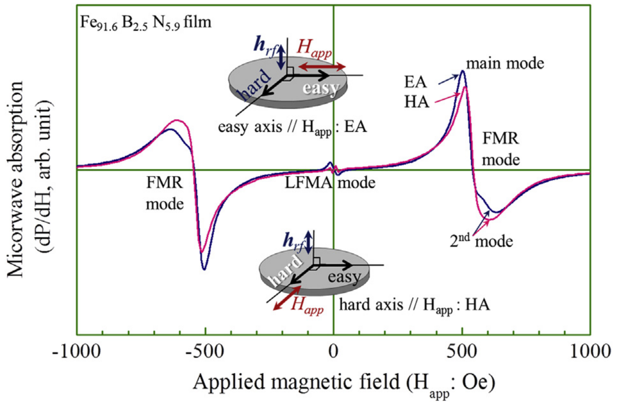

Fig. 1. The derivative microwave absorption; The FMR appear at around ±500 Oe and LFMA signals at around a zero field for in-plane easy and hard direction of $Fe_{91.6}B_{2.5}N_{5.9}$ magnetic film, respectively.

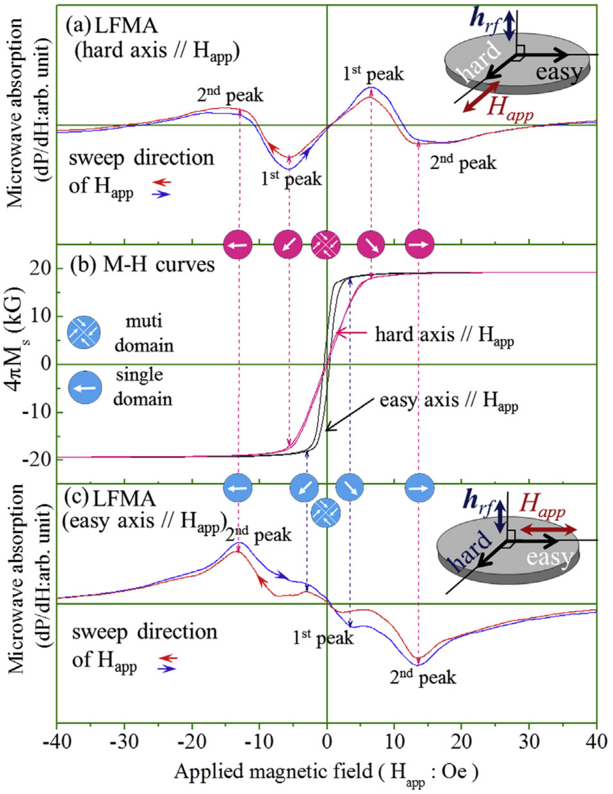

Fig. 2. The M–H hysteresis curves (b) and the derivative microwave absorption signals; The LFMA signals at in-plane hard (a) and easy (c) direction of $Fe_{91.6}B_{2.5}N_{5.9}$ magnetic film, respectively.

Fig. 3 shows the FMR and LFMA signals for a multi-layered GMR film with exchanged coupled layers. The spectrum for the easy axis showed two distinct resonance peaks corresponding to the uniform