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Microwave magnetic properties of the oriented CoIr soft magnetic film with negative magnetocrystalline anisotropy

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ABSTRACT

The natural resonance frequency of the oriented soft magnetic thin film with in-plane uniaxial anisotropy and negative magnetocrystalline anisotropy (K_u^{grain}) was investigated in hcp structure of $Co_{80}Ir_{20}$ film with the *c*-axis perpendicular to the film plane. As the out-of-plane anisotropy field contained the field produced by negative K_u^{grain} besides the demagnetization field, the natural resonance frequency was enhanced dramatically compared with the conventional soft magnetic film without magnetocrystalline anisotropy. Through solving the equation of magnetization precession, the initial permeability of this kind of film was shown to be unrelated to the negative K_u^{grain} and yet determined by the in-plane uniaxial anisotropy field and the saturation magnetization of the film.

1. Introduction

Microwave magnetic properties of soft magnetic films have attracted much attention due to their wide applications in electronic devices such as magnetic head, micro-inductor, and electromagnetic noise absorber as operation frequency approaches the gigahertz region [1,2]. The basic demands for microwave soft magnetic films include high saturation magnetization M_s which is necessary to get a high initial permeability μ_i, and the appropriate in-plane uniaxial anisotropy field H_u which is required to support a uniform precession axis of magnetization and to possess a high ferromagnetic resonance frequency f_r (cut-off frequency). In previous publications, the microwave magnetic properties of Fe- and Co-based magnetic films with in-plane uniaxial anisotropy and high M_s have been widely studied [3–11]. Through summarizing these works, a conclusion can be obtained that nearly all the reported materials have one common characteristic in magnetic parameters: their crystalline anisotropy can be negligible. As the magnetocrystalline anisotropy of the material is not considered, the out-of-plane anisotropy field of the film is equivalent to the demagnetization field $4\pi M_s$. If in-plane uniaxial anisotropy field H_u satisfies $H_u \ll 4\pi M_s$, the natural resonance frequency f_r is described by[9,10]

$$f_r = \frac{\gamma}{2\pi}\sqrt{H_u 4\pi M_s}. \quad (1)$$

This resonance condition is the famous Kittel equation [10]. f_r is determined only by the in-plane uniaxial anisotropy field H_u and demagnetization field $4\pi M_s$. Initial permeability μ_i is expressed as

$$\mu_i = 1 + \frac{4\pi M_s}{H_u}, \quad (2)$$

and $4\pi M_s$ in this equation is the saturation magnetization.

For higher operation frequency of electronic devices, microwave soft magnetic film possessing higher f_r is required. From Eq. (1), the increase of f_r for the film without consideration of magnetocrystalline anisotropy is achieved only by the increase of H_u when M_s is been fixed. In experiment, this has been accomplished in many groups through adjusting the sputtering tilt angle or introducing an in-plane bias field [3,12–15]. However, the undesirable result is that all μ_i in the reported work decreases with the increase of f_r. The decrease of μ_i is easily understood by Eq. (2) and unfavorable for the magnetic electronic devices because it will decrease the write field of the magnetic head and the inductance of micro-inductors. From Eqs. (1) and (2), we know that the increase of f_r inevitably results in the decrease of μ_i in conventional microwave soft magnetic films without consideration of magnetocrystalline anisotropy. If we want to keep high μ_i with the increase of f_r, a new kind of microwave soft magnetic film should be explored. In this work, we study the microwave magnetic properties of a type of soft magnetic film in which strong negative magnetocrystalline anisotropy K_u^{grain} is introduced.

2. Description of oriented $Co_{80}Ir_{20}$ soft magnetic film with negative magnetocrystalline anisotropy

$Co_{1-x}Ir_x$ ($x\sim0.2$) soft magnetic alloy with hcp structure has been reported to have strong negative K_u^{grain}($\sim-10^6$ erg/cm^3) and

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negligible K_4 ($\sim 10^2$ erg/cm^3), and has a high M_s [16,17]. For negative K_u^{grain}, the *c*-axis becomes a hard axis of magnetization and the magnetic moments prefer to lie in the *c*-plane. If an oriented CoIr magnetic film with the *c*-axis of grains perpendicular to the film plane is fabricated, both the demagnetization field and magnetocrystalline anisotropy field compel magnetic moments to lie in the film plane, resulting in the enhancement of the total out-of-plane anisotropy field. On the other hand, as K_4 is very small, the soft magnetic properties are held in the film plane and the in-plane anisotropy field is dominated by the induced in-plane uniaxial anisotropy field produced during the fabrication process. In Ref. [16], the potential application of the CoIr soft magnetic film with negative K_u^{grain} as a new type of soft underlayer in perpendicular magnetic recording was studied. Owning to negative K_u^{grain}, the suppression of spike noise and wide adjacent track erasure was achieved. Additionally, the possible realization of high natural resonance frequency and magnetic susceptibility in superparamagnetic CoIr nanoparticle with negative K_u^{grain} has been reported [18,19]. Here we fabricated oriented $Co_{80}Ir_{20}$ soft magnetic film with in-plane uniaxial anisotropy and negative K_u^{grain}. The relationship between the microwave magnetic properties and the anisotropy fields including the in-plane uniaxial anisotropy field and the total out-of-plane anisotropy field was investigated. Through this work, we want to introduce a method to improve the microwave properties of soft magnetic films.

3. Experiment

The oriented $Co_{80}Ir_{20}$ film with a thickness of 50 nm was fabricated by dc magnetron sputtering Co and Ir targets. The base pressure of vacuum was smaller than 5×10^{-5} Pa and sputter pressure was 0.3 Pa. Si wafer with surface oxidation was used as substrate. To obtain the *c*-axis perpendicular to the film plane, a Ta(10 nm)/Pt(10 nm)/Ru(10 nm) sequence was sputtered on the substrate in advance as a seed layer. In the sputtering process, the tilting sputter method was used to induce in-plane uniaxial anisotropy [12]. VSM, SQUID, and FMR were used to characterize its static and microwave magnetic properties.

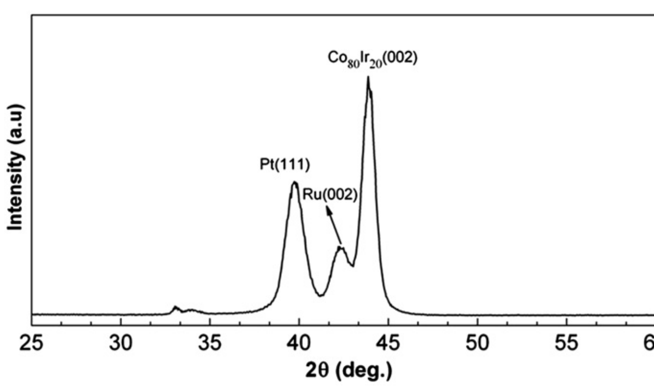

Fig. 1. The XRD pattern of the sample by the powder method.

4. Results and discussion

Fig. 1 shows the XRD pattern of the $Co_{80}Ir_{20}$ film, which was measured by the powder method. There are only (1 1 1) peak of Pt and (0 0 2) peak of Ru and $Co_{80}Ir_{20}$. On the (1 1 1) plane of Pt, hcp Ru grows orientedly with its (0 0 2) plane parallel to the film. On the (0 0 2) plane of Ru with hcp structure, oriented growth of $Co_{80}Ir_{20}$ film with *c*-axis perpendicular to the film plane is successfully realized.

Hysteresis loops measured in the film plane with the applied field parallel and perpendicular to the easy axis are shown in Fig. 2(a). The film has good soft magnetic properties and obvious in-plane anisotropy due to the tilting sputter. The initial magnetization curve perpendicular to the film, measured by SQUID at room temperature is shown in Fig. 2(b). The sample is not saturated until the applied magnetic field reaches 25.4 kOe. At room temperature, the measured saturation magnetization of the $Co_{80}Ir_{20}$ film is 988 G which agrees well with the reported M_s of $Co_{80}Ir_{20}$ [17], so the demagnetization field $4\pi M_s = 12.42$ kOe. When the applied field visibly exceeds the demagnetization field, the sample is still not saturated. This is ascribed to the strong negative K_u^{grain} of $Co_{80}Ir_{20}$ grains, which compels magnetic moments to lie in the *c*-plane of the grains. In this case, the out-of-plane anisotropy field contains the demagnetization field and the equivalent magnetocrystalline anisotropy field. The total out-of-plane anisotropy field H_θ is obtained by calculating the area between the magnetization curves parallel and perpendicular to the film plane, and the value is 21.3 kOe. Since the demagnetization field is related only to the shape of the sample, it has been fixed as $4\pi M_s = 12.42$ kOe. The equivalent magnetocrystalline anisotropy field $H_u^{grain} = |2K_u^{grain}/M_s| = 21.3$ kOe–12.42 kOe = 8.88 kOe.

Fig. 3(a) gives the FMR differential spectrum of the sample at a frequency of 8.97 GHz. The microwave magnetic field is in the film plane and perpendicular to the easy axis, and the applied magnetic field is parallel to the easy axis. A single ferromagnetic resonance occurs at 0.38 kOe. The circle dots in Fig. 3(b) are the resonance field dependence of angle between the applied magnetic field and the easy axis. All the resonance fields were measured with the applied magnetic field in the film plane. The

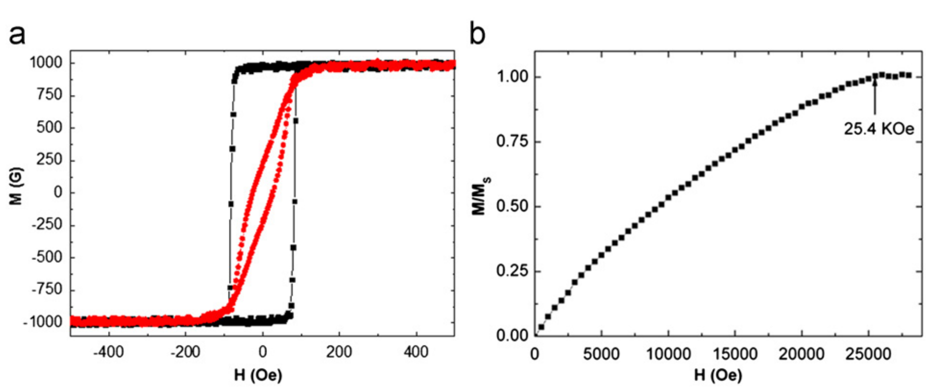

Fig. 2. (a) Hysteresis loops in the film plane with the applied field parallel and perpendicular to the easy axis and (b) the initial magnetization curves along the easy axis in film plane and perpendicular to the film plane.