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Comparison of hysteresis loop area scaling behavior of Co/Pt multilayers: Discrete and continuous field sweeping

Djati Handoko [a], Sang-Hyuk Lee [a], Kyung Min Lee [b], Jong-Ryul Jeong [b], Dong-Hyun Kim [a,*]

[a] Department of Physics, Chungbuk National University, Cheongju 361-763, South Korea
[b] Department of Material Science and Engineering and Graduate School of Green Energy Technology, Chungnam National University, Daejeon 305-764, South Korea

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ABSTRACT

We have investigated the hysteresis loop shape changes with discrete and continuous magnetic field sweeping for Co/Pt multilayers with a perpendicular magnetic anisotropy. The hysteresis loop shape was observed by measuring a polar magneto-optical Kerr effect. The loop area has been found to increase rapidly with an increase of the field step size as well as the sweeping frequency until the area reaches a maximum. The increase of the loop area has been analyzed based on the Steinmetz law, where a loop area scaling exponent determined from discrete field sweeping is compared to a scaling exponent from continuous field sweeping. The dynamic coercivity behavior with respect to discrete and continuous field sweeping is analyzed together with the loop area scaling behavior, suggesting that details of magnetic configuration disorders do not modify the loop area scaling exponent.

1. Introduction

Hysteresis is a very useful phenomenon in characterizing the magnetic properties of magnetic devices and materials due to its nondestructive capability in measuring a magnetic response [1,2]. The magnetic hysteresis loop also provides an interesting playground in studying dynamic properties of various ferromagnetic systems [3]. The measured magnetic hysteresis loop under a periodically driving magnetic field includes a rich context of information represented by a hysteresis loop shape and a loop area. There have been numerous studies both experimentally [4–7] and theoretically [8–12] to understand the hysteretic phenomenon in magnetic systems, where it has been found that the loop area varies as a power law with respect to the field sweeping rate Ω and the sweeping amplitude H_0.

In general, a hysteretic response arises from a delayed response or dissipation of the system [3], which leads to a rate-dependent hysteresis behavior. Recently, dynamic magnetic hysteresis loop behavior [13] and subsequent Barkhausen noise characteristics [14] have been theoretically investigated based on the loss separation model. One of most important parameters in analyzing the hysteresis behavior is a scaling exponent in the power-law behavior of the loop area. It has been well known that the loop area follows the Steinmetz law [11,15], where a dynamic scaling law for the loop area A is satisfied as in Eq. (1).

$$A \sim A_0 + H_0^{\alpha} \Omega^{\beta}, \quad (1)$$

where A_0 is a nonzero adiabatic loop area. α and β are the scaling exponents for the field amplitude and the field frequency, respectively. It has been known that there are two regimes of the scaling behavior in the magnetic system under a periodic driving force [11], where a 'slow' regime is considered to be a dynamical regime for the driving field frequency lower than the loop area resonance frequency and a 'fast' regime is for the driving field frequency greater than the loop area resonance frequency [16–18].

However, to our knowledge, no study has been devoted to the effect of the field step size to the hysteresis loop scaling behavior. In the same time, most of the experiments adopt the digital interfacing in the measurements using a personal computer and thus, there is, always in this case, an effect of the discrete field step size. Considering the rate-dependent hysteresis scaling behavior, the discrete field step size effect may not be simply neglected. In driving a ferromagnetic system with a cycling external magnetic field, the cycling field is composed of sequential stepwise increases or decreases, where two time scales are involved, i.e. a timescale of a transient response time of a power supply Δt_{tr} and a timescale of an interval among field steps Δt. The transient response timescale of a conventional power supply, when the power supply is ordered to change an output current from zero to full scale to an electromagnet for generation of a magnetic field, is about 1 ms or faster depending on detailed power supply specifications. Then,

* Corresponding author: Tel.: +82 43 261 2268; fax: +82 43 274 7811.
E-mail addresses: donghyun@chungbuk.ac.kr, donghyun@cbnu.ac.kr (D.-H. Kim).

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the discrete sweeping rate $\left(\frac{dH}{dt}\right)_{disc}$ is expressed as

$$\left(\frac{dH}{dt}\right)_{disc} = 4\frac{(\Delta H)^2}{H_0(\Delta t + \Delta t_{tr})} \tag{2}$$

Since we fixed Δt to be 110 ms and Δt_{tr} is around 1 ms for all measurements, $\left(\frac{dH}{dt}\right)_{disc}$ is mainly determined by the field step size.

On the other hand, so far, most of experiments have been carried out for the samples with in-plane magnetic anisotropy [4–6,16–18], and very few studies have been devoted to the magnetic films with the perpendicular magnetic anisotropy [19]. Very recently, for perpendicular anisotropy materials such as Co/Pt multilayers, discovering a non-reproducibility of minor loop curves has become a subject of substantial interest [20–21]. Considering the essential difference of a different symmetry due to the different easy axis, there is no doubt that any investigation on the loop area scaling behavior for samples with the perpendicular magnetic anisotropy will be helpful in extending our understanding of the underlying mechanism of the Steinmetz law.

The aim of this study is to intensively investigate the hysteresis loop scaling behavior of Co/Pt multilayer film with the perpendicular magnetic anisotropy. In case of the field-step dependent hysteresis loop behavior, magnetic field step size was systematically varied with keeping the same interval time for each field step as shown in Fig. 1(a), which is compared to the case of continuous field sweeping. Dynamic coercivity under continuous and discrete sweeping was also determined to extensively comprehend the loop area scaling behavior.

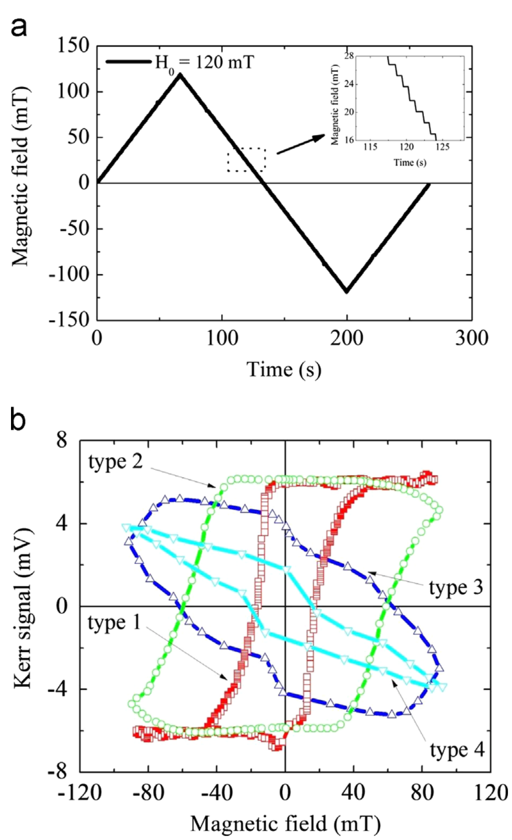

Fig. 1. (a) Example of a cycle of discrete sweeping field profile with H_0=120 mT and ΔH=1.6 mT. (b) Example of hysteresis loop shape change with respect to the field step size of 0.71 mT (type 1), 4.2 mT (type 2), 9.9 mT (type 3), and 14 mT (type 4) at an amplitude of 90 mT in case of a discrete sweeping for (5-Å Co/8-Å Pt)$_{10}$ sample.

2. Experiment

Co/Pt multilayer films were deposited on the Si substrate at an ambient temperature by means of the DC magnetron sputtering. The typical deposition rate was 0.5 Å/s for Co and 1.1 Å/s for Pt with an applied power of 30 W and a target-to-substrate distance of 100 mm. (X-Å Co/8-Å Pt)$_{10}$ multilayer films (X=5–7) were examined. Hysteresis loop measurement has been carried out by polar magneto-optical Kerr effect (P-MOKE) with a green diode laser of 532-nm wavelength and 40 mW power. The P-MOKE signal is achieved by photodiode and processed by transimpedance amplifier with a lock-in frequency of 200 Hz to enhance a signal-to-noise ratio. The details of the noise properties for the present sample are described elsewhere [22]. The current source for coil is a regulated DC power supply. We checked our results for two models of power supply (Agilent 6030A and NF EC1000S). The field step size has been varied from 0.71 to 46.8 mT, which are corresponding to the output power supply current of 0.5 to 100 mA, respectively. The amplitude of the cycling external field was varied from 90 to 140 mT. To avoid a training effect, we magnetized and demagnetized the sample more than 10 times before carrying out the P-MOKE experiment. The hysteresis loop is measured 10 times and averaged at each field profile.

3. Result and discussion

In Fig. 1(b), a series of hysteresis loops measured with variation of field steps are illustrated for (5-Å Co/8-Å Pt)$_{10}$ multilayer and the field amplitude of 90 mT. The hysteresis loop shape can be categorized into four types, which is in accordance with the previous report with changing frequencies of continuous sweeping field [10], namely: first, at a very low field step size (ΔH=0.71 mT), the hysteresis loop shape is square-like with a clear sign of saturation (type 1). At a little bit higher field step size (ΔH=4.2 mT), square-shaped hysteresis loop starts to change with a rounded corners at the saturation and the loop area is enlarged significantly (type 2). At a further higher field step size (ΔH=9.9 mT), the parallelogram-like hysteresis loop is observed (type 3). Finally the hysteresis loop collapses almost into a straight line, type 4 (ΔH=14 mT). The overall slope of the almost flattened loop of type 4 has an opposite sign compared to other cases of types 1 and 2, clearly implying the existence of the response delay of the magnetization with relative phase to the driving field. Similar trend is observed for all samples with different field amplitudes of 120 and 140 mT.

We have checked the reproducibility of the measured hysteresis loops and areas. As demonstrated in Fig. 2, for all types, the loop shape and the area were found to be reproducible within the error range for 10 successive measurements in all types, which is different from the recent works [20,21], where a non-reproducible evolutionary and cumulative minor loop behavior for successive loop measurements have been reported. The origin of non-reproducible minor loop behavior might be considered as the tiny left-over magnetic domain structure that plays a role in a magnetization reversal during the repeated field cycling. There might be some possible region in a parameter space spanned by field step and field amplitude, where we may similarly observe the non-reproducible evolutionary behavior. Considering that all the results here do not exhibit the non-reproducible behavior, our parameter space might be off from the possible observation region. Our work is mainly focusing on examining the difference of the discrete and continuous field sweeping cases and we believe that our discussion and conclusion is not substantially affected by the non-reproducible evolutionary and cumulative minor loop behavior.