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Characterization of magnetic properties in Co/Pd multilayers by Hall effect measurement

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Abstract

A Hall voltage measurement has been carried out by adopting four-probe technique to characterize the magnetization reversal characteristics in ultra-thin ferromagnetic films of (2–Å Co/11–Å Pd)$_n$ multilayer having different number of repeats n, where the anisotropy constant and saturation magnetization increased with increasing the number of repeats n. The Hall voltage exhibited a clear hysteresis behavior of Co/Pd multilayer films with sweeping the external magnetic field, and the field angle dependence and the temperature dependence of the magnetization reversal characteristics have been investigated using the Hall voltage hysteresis.

Keywords: Multilayer; Hall voltage; Temperature dependence

1. Introduction

Ferromagnetic thin films are of great interest in recent years due to the possibilities of the magnetic applications as well as their novel magnetic properties [1–4]. As the appropriate thickness of those films for achieving the high performance of the magnetic applications becomes thinner below a few nanometer and/or the artificially patterned structure on those films becomes smaller below a micrometer, it becomes hard to precisely measure the magnetization reversal characteristics by using the conventional methods, such as vibrating sample magnetometer (VSM) or magneto-optical Kerr effect magnetometer, due to the weak signal from the small volume of ultra-thin films compared with substrate or sample holder.

The anomalous Hall effect measurement technique has been recently developed to measure the magnetization reversal characteristics of ultra-thin ferromagnetic films, largely motivated by the fact that the anomalous Hall voltage is inversely proportional to the film thickness [5–7]. In this study, we present the experimental results on the magnetization reversal characteristics of ultra-thin Co/Pd multilayer films, by means of a Hall effect measurement technique, and have investigated the angle and the temperature dependences of the magnetic hysteresis loops based on the magnetic field dependence of the Hall voltage.

2. Experiments

A number of (2–Å Co/11–Å Pd)$_n$ samples with varying the number of repeats n were prepared on glass substrates under a base pressure of 2×10^{-7} Torr at the ambient temperature [8]. The multilayer structure was achieved by alternatively exposing the substrate to two e-beam sources via a rotating substrate holder. Typical deposition rates of 0.3 Å/s for Co and 0.5 Å/s for Pd, monitored by two corresponding quartz crystal sensors, were kept constant within a 10% fluctuation. Difference between the intended thickness and the actual thickness determined from low-angle X-ray diffraction was turned out to be less than 4%. Low-angle X-ray diffraction studies using CuK$_\alpha$ radiation revealed that all samples had distinct peaks indicating an existence of

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the multilayer structure. High-angle X-ray diffraction studies showed that the samples grew along the [1 1 1] cubic orientation. All the samples have perpendicular magnetic anisotropy and show $M-H$ hysteresis loops of unit squareness.

The Hall voltage V_H has been measured by adopting the four-probe method under a constant current mode of 1 mA. With sweeping the external magnetic field H, we could measure the Hall voltage hysteresis loops i.e. V_H-H loops, where the Hall voltage corresponds to the magnetization component normal to the film plane. For the field angle dependence study, the measurement system was equipped by a sample rotator varying in the range of the angle θ from 0° to 90°, where θ is the angle between the applied magnetic field and the film normal. And also, the sample stage was embedded in a temperature stage within the range from 50 to 300 K, which enable us to investigate the temperature dependence of the magnetization reversal characteristics.

3. Results and discussion

All the samples in this study have perpendicular magnetic anisotropy and show $M-H$ hysteresis loops of unit squareness. In Fig. 1, we plot (a) the anisotropy constant K_U measured by null-type torque magnetometer and (b) the saturation magnetization M_S measured by VSM, respectively, for samples having different number of repeats, where K_U and M_S were normalized by unit Co volume, respectively. Both the anisotropy constant and the saturation magnetization increased with increasing the number of repeats, which evidenced the structural change in film morphology among the samples. The saturation magnetization was found to be larger than that of the bulk Co due to the induced magnetization of Pd layers.

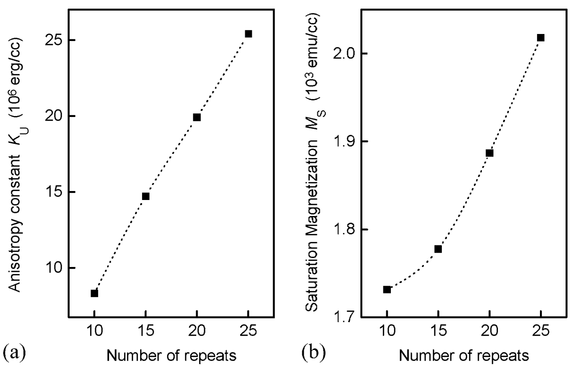

Fig. 1. (a) Anisotropy constant K_U and (b) saturation magnetization M_S of (2–Å Co/11–Å Pd)$_n$ samples with respect to the number of repeats n. Both the values were normalized by unit Co volume.

Interestingly, the Hall voltage V_H was found to be sensitive enough to measure the magnetization reversal characteristics in ultra-thin ferromagnetic films. Fig. 2 shows the V_H-H hysteresis loops of (2–Å Co/11–Å Pd)$_{15}$ sample, where each curve was measured under different angle θ from 0° to 90° as denoted in the figure. It would be noticed that the Hall voltage exhibits a clear hysteresis behavior with a high signal-to-noise ratio. The shape of the loops is systematically changed from easy- to hard-axis behaviors with changing the field angle θ from 0° to 90°, which is well matched to the $B-H$ hysteresis behavior, since the Hall voltage V_H is proportional to the magnetic induction B in the magnetic thin films [9]. The increment of the coercivity field H_C with respective to the field angle can be understood within the context of an irreversible process of the domain wall [10], where the coercivity field is inversely proportional to the cosine of the field angle.

In Fig. 3, we plot the coercive field H_C with respect to the number of repeats n. The figure shows that the

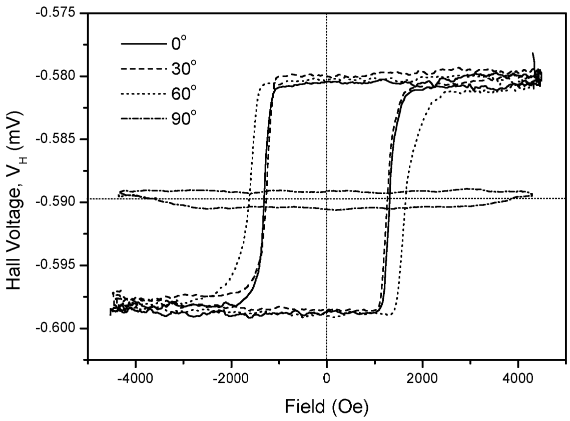

Fig. 2. V_H-H hysteresis loops under various field angle θ for (2–Å Co/11–Å Pd)$_{15}$ sample.

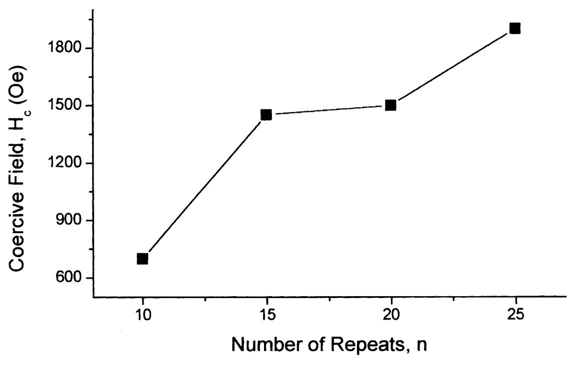

Fig. 3. Dependence of H_C with respect to the number of repeats n for (2–Å Co/11–Å Pd)$_n$ samples.

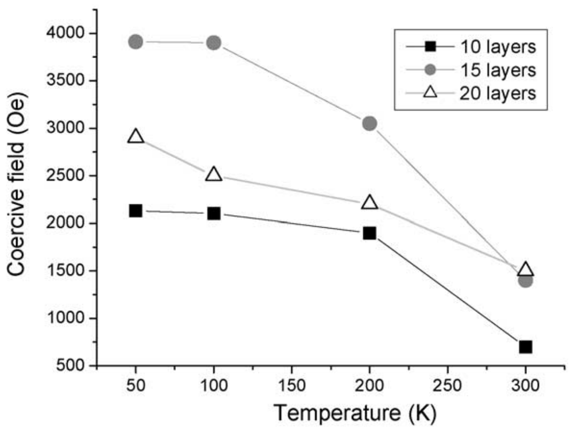

Fig. 4. Temperature dependence of H_C for (2–Å Co/11–Å Pd)$_n$ samples with different number of repeats n.

coercive field largely increased from 650 to 1900 Oe with increasing the number of repeats n from 10 to 25. This increment of the coercive field could be understood by considering either the increment of the uniaxial anisotropy or the increment of the wall-pinning effect due to the possible accumulation of the structural defects at interfaces with increasing the number of repeats. The rate of increment was found to be larger in the samples of thin Co sublayer structure of which exhibits the contrasting behavior from the wall-motion dominated to nucleation dominated magnetization reversal behaviors with increasing the number of repeats [11].

The temperature dependence of the magnetization reversal characteristics was investigated. Fig. 4 shows the change of the coercive field of (2–Å Co/11–Å Pd)$_n$ samples with respect to the measurement temperature. All the samples exhibited that the coercive field decreased with increasing the measurement temperature. It might be understood because the thermal activation energy increases with increasing the temperature, where the magnetization reversal takes place by the thermally activated process overcoming the reversal energy barrier for domain nucleation and wall-depinning processes.

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