New measurement techniques to determine magnetization and coercivity using a torque magnetometer

Jeen Hur and Sung-Chul Shin
Department of Physics, Korea Advanced Institute of Science and Technology, Kusung-Dong, Yusung-Gu, Taejon 305-701, Korea

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We have developed new techniques to measure the magnetization and the coercivity of a uniaxial magnetic material using a torque magnetometer. The magnetization could be measured from the linear dependence at the low-field regime in a plot of the torque versus the applied magnetic field, where the direction of the applied field was perpendicular to the uniaxial orientation. The coercivity could be obtained by taking the value of the applied field where the torque is zero, when the direction of the applied field was $(180+\delta)$ degrees from the uniaxial orientation. The techniques were applied to determine the magnetizations and the coercivities of several Co/Pd multilayer thin films. The results were confirmed to be similar within a 2% difference to those obtained by a vibrating sample magnetometer.

The measurements of the magnetization and the coercivity are essential to understand and develop magnetic materials. A vibrating sample magnetometer (VSM) is commonly used to measure those quantities.[1] Several torque magnetometric methods have been suggested for determination of the saturation magnetization as well as the uniaxial anisotropy energy by Miyajima *et al.*,[2] Wielinga,[3] and Pastor *et al.*[4] A major disadvantage in those torque magnetometric methods is the fact that a high applied field comparable to the anisotropy filed is required to achieve an accurate measurement. Thus, the methods are not practical for a sample having a high anisotropic field. In this letter, we present new measurement techniques to determine the magnetization and the coercivity using a torque magnetometer.

In our method, a magnetic material is assumed to have a uniaxial anisotropy normal to the shape anisotropy. Considering only the first-order anisotropy constant K_u, the magnetostatic energy E and the torque τ of the system under an applied field H may be expressed by

$$E=K_u \sin^2 \theta+K_s \cos^2 \theta-MH\cos(\phi-\theta)$$

$$=K_s+(K_u-K_s)\sin^2 \theta-MH\cos(\phi-\theta), \quad (1)$$

$$\tau=-MH\sin(\phi-\theta), \quad (2)$$

where K_s is the shape anisotropy and M is the magnetization.[5] Here, θ and ϕ are the orientations of the magnetization and an applied field, respectively, measured from the easy axis as depicted in Fig. 1. Since the magnetization vector will be oriented to minimize the total energy of the system, $(\partial E/\partial\theta)=0$ at equilibrium. Therefore, from Eqs. (1) and (2) the torque τ at equilibrium is given by

$$\tau=-K\sin 2\theta, \quad (3)$$

where $K=K_u-K_s$.

The experimental procedure for the magnetization measurement is as follows: a magnetic field larger than the coercivity of a sample is applied along the easy-axis orientation as seen in Fig. 2(a), and then the torque is measured as a function of the applied field after setting the direction of the field to be perpendicular to the easy-axis orientatio[n] as shown in Fig. 2(b). Since $\theta \ll 1$ for an applied field r[e]gime much lower than the anisotropic field, Eq. (2) b[e]comes approximately

$$\tau/H=-M(1-\tfrac{1}{2}\theta^2+\cdots). \quad (4)$$

Hence, considering the first-order approximation, the ma[g]netization can be obtained from the slope of a torque curv[e].

From Eqs. (3) and (4) the difference between the tr[ue] value M and the first-order approximation value $-\tau/H$ [is] estimated by

$$M+\tau/H\simeq\tfrac{1}{2}M(H/H_k)^2, \quad (5)$$

where H_k represents the anisotropy field of $2K/M$. So, [the] uncertainty of the first-order approximation is depende[nt] on a ratio of the applied field to the anisotropy field. [It] should be emphasized that a better accuracy in the ma[g]netization measurement is achieved for a material having [a] higher anisotropic field by using the present method, whic[h] yields a striking difference compared to the methods pu[b]lished so far.[2-4] Taking an example in the case of $(H/H_k)<0.1$, the first-order approximation of the prese[nt] method provides less than a 0.5% inaccuracy in the me[a]surement of the magnetization. It should be mention[ed]

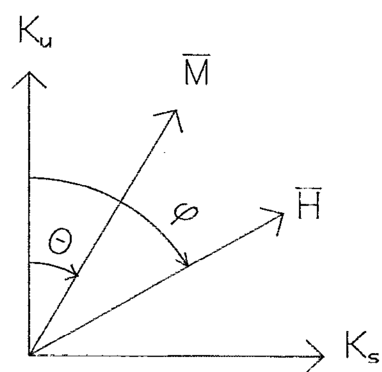

FIG. 1. Coordinates in torque magnetometry. Here, K_u represents [the] uniaxial anisotropy, K_s the shape anisotropy, and M the magnetizatio[n].

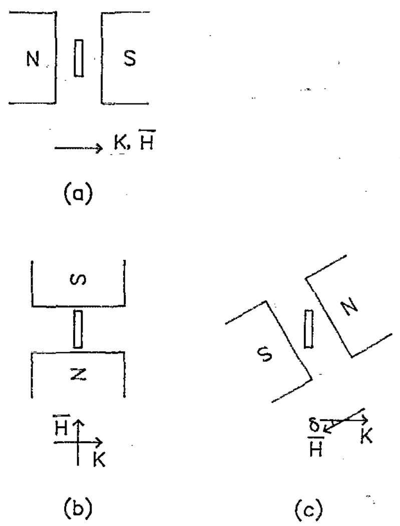

FIG. 2. The configurations (a) to initially saturate a sample, (b) to measure the magnetization, and (c) to measure the coercivity.

that an exact alignment of an applied field along the normal-to-easy-axis orientation is important to maintain an accuracy in this method. Suppose that the direction of the applied field is misaligned by ϵ degrees from the normal-to-easy-axis orientation, then an uncertainty is estimated to be about $\frac{1}{2}M(H/H_k-\epsilon)^2$.

The method to measure the coercivity is as follows: a magnetic field is applied along the easy-axis orientation of a sample to make it saturate, and then the torque is measured with increasing the applied field at the field direction $\phi=(180+\delta)°$, as shown in Fig. 2(c). Under this configuration the torque τ is expressed by $\tau=HM\sin(\delta-\theta)$ from Eq. (2) and, therefore, τ has a positive to a negative value via zero with increasing applied magnetic field. When τ is zero, the magnetization should be zero since $H\sin(\delta-\theta)$ cannot be zero except $\delta=0$ or $\pm\frac{1}{2}\pi$. So, one can obtain the coercivity at this orientation by taking the applied field where $\tau=0$.

Our new method was applied to measure several Co/Pd multilayer thin films having the same total thickness of 300 Å but different bilayer thicknesses. Details of the sample preparation technique have been reported elsewhere.[6] A homemade torque magnetometer,[7] having a 0.002-dyn cm resolution in the measurement range of 5 dyn cm, has been used. The small signal from the sample holder and uncoated substrate was subtracted out for the torque measurement.

Figure 3 is a plot of the torque τ versus the applied field H for the magnetization measurement of a (4-Å Co/9-Å Pd) sample composed of 4-Å-thick Co and 9-Å-thick Pd sublayers. A linear dependence of τ on H can be seen from the figure in a low-field regime. The linear slope in the plot corresponds to the magnetization as described earlier and it turns out to be 351 emu/cm^3 for the sample. In this figure, the applied field where the torque becomes zero is the anisotropy field H_k of this particular sample.

Considering a 2×10^{-3}-dyn cm resolution of the torque magnetometer used in the measurement, a resolution of the magnetization using the present method is given by $2\times10^{-2}/H_k$ dyn cm/Oe, and thus a resolution of 1×10^{-6} emu could be achieved in the case of $H_k=20$ kOe.

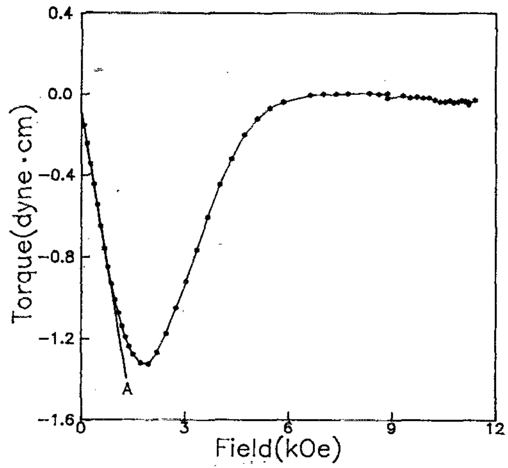

FIG. 3. A plot of the torque vs the applied field for the measurement of the magnetization of a (4-Å Co/9-Å Pd) multilayer.

The result of the coercivity measurement for the (4-Å Co/9-Å Pd) sample is illustrated in Fig. 4, taking $\delta=9°$. The applied field of 2.78 kOe, where the torque is zero, is the coercivity of the sample since the magnetization must be zero at a zero torque. It should be noted that a slope of the torque around $\tau=0$ in Fig. 4 is related with the squareness of a M-H loop; a better squared loop shows a more rapid passage through $\tau=0$. Details of the quantitative analysis will be published elsewhere.[8]

In Table I, we compare the experimental values of the magnetizations and the coercivities of four Co/Pd multilayer thin films measured by the present method and a VSM. Except for the magnetization of the (6-Å Co/9-Å Pd) sample, the values obtained by our new method are well matched to those measured by the VSM to within a 2% difference. The magnetization of the (6-Å Co/9-Å Pd) sample obtained by our method turned out to be the remnant magnetization, which was confirmed by a VSM mea-

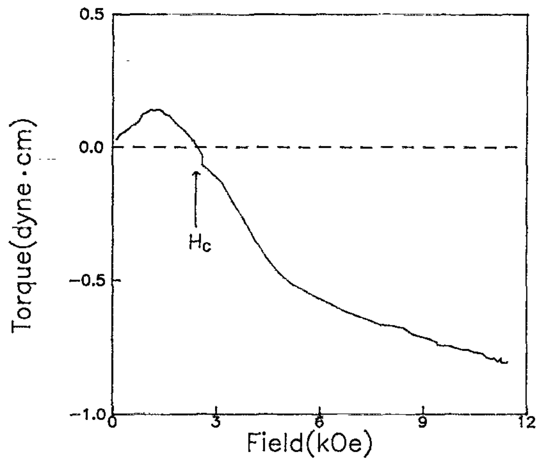

FIG. 4. A plot of the torque vs the applied field for the measurement of the coercivity of the (4-Å Co/9-Å Pd) multilayer.

TABLE I. Comparisons of the magnetization and the coercivity measured by our new method and a VSM.

	Present method		VSM	
Sample ID	M (emu/cm^3)	H (kOe)	M (emu/cm^3)	H (kOe)
2-Å Co/6-Å Pd	375	3.24	379	3.23
2-Å Co/9-Å Pd	311	3.05	306	3.12
4-Å Co/9-Å Pd	351	2.78	348	2.75
6-Å Co/9-Å Pd	168	0.77	378	0.78

surement; thus, it is believed that a multidomain structure existed in the sample.

In conclusion, we have developed a new method to measure the magnetization and the coercivity of a uniaxial magnetic material using a torque magnetometer. A better accuracy and resolution in the measurement of the mag tization could be achieved for a larger anisotropy fie which yields a sharp contrast with the existing methods should be mentioned that an accuracy of the measurem is negligibly affected by including higher-order terms of anisotropy energy.

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