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An approach to determine the easy axis of magnetic film by anisotropic magnetoresistance measurements

Wei Du[1], **Xiaoli Tang**[1,3], **Mengli Liu**[1], **Hua Su**[1], **Genliang Han**[2,3] **and Qihai Lu**[2]

[1] State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu, Sichuan 610054, People's Republic of China

[2] Key Laboratory of Sensor and Sensing Technology of Gansu Province and Institute of Sensor Technology, Gansu Academy of Sciences, Lanzhou 730000, People's Republic of China

E-mail: tangtang1227@163.com (X Tang) and genlhan@vip.sina.com (G Han)

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Abstract

A series of Ta/NiCo/Ta films was grown through DC-sputtering. During deposition, a constant magnetic field was applied along the substrate in different directions to induce different orientations of the easy axis. Three different magnitudes of external fields were applied in the angle-dependent anisotropic magnetoresistance (AMR) measurements of the samples. Through an effective analysis, the angle-direction extracted via the intersection of three angle-dependent AMR curves was confirmed as the easy axis. Compared to the normal methods applied to achieve the easy axis, the results are convincing. This new method provides an effective, convenient and low cost way of studying magnetic materials and devices.

Keywords: angle-dependent, anisotropic magnetoresistance, easy axis, magnetic materials, measurement

(Some figures may appear in colour only in the online journal)

1. Introduction

Ferromagnetic materials exhibit intrinsic 'easy' and 'hard' directions of the magnetization. Normally, it is called magnetic anisotropy. The magnetic anisotropy is a technological and fundamental important property of magnetic materials and is regarded as the basic parameter in studying magnetic films. It is also important in many devices based on the magnetoelectric effect. For example, the voltage-controlled magnetic random access memories [1, 2], magnetic sensors [3], spin-logic circuits [4–6], and microwave devices [7]. Until now, various methods, such as magnetotransport measurements, magnetic hysteresis loop determination via vibrating sample magnetometer (VSM) [8, 9], ferromagnetic resonance [7], and rotational magneto-optic Kerr effect [10–14], have been developed to characterize magnetic anisotropy. These methods involve professional equipment, advanced technology, and are not easy to achieve in every laboratory.

The anisotropic magnetoresistance (AMR) effect is a basic effect in magnetic films. The resistance value of magnetic film depends on the relative direction of the current I and the magnetization M. The resistance achieves its maximum ($R_{//}$) and minimum ($R_{\perp}$) values when the current is parallel and perpendicular to the magnetization, respectively. Therefore, the AMR effect supplies a direct way to reveal the direction of the magnetization, magnetization reversal, and the magnetic anisotropy [15–18]. It has already been applied as a simple method for determining the coercivity of single layer magnetic film and ferromagnetic/antiferromagnetic exchanged bias film [19, 20]. It has also been proposed to decide the easy axis of magnetic film, especially in studying multiferroic heterostuctures [19, 21]. Previous studies have measured the angle-dependence of AMR and treated the maximum AMR value as the easy axis. However, some studies have argued that the

[3] Author to whom any correspondence should be addressed.

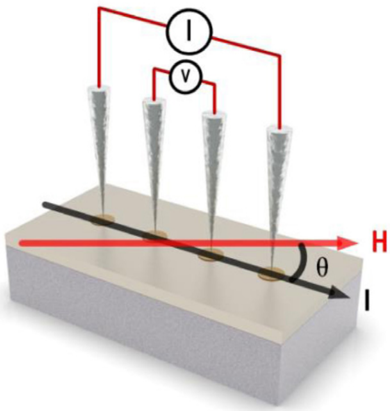

Figure 1. Experimental geometry for magnetoresistance measurements. The external magnetic field can be rotated in film plane.

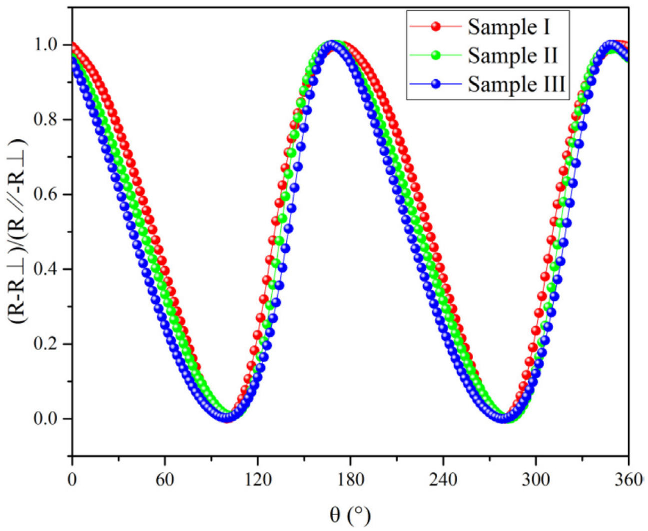

Figure 2. Angle θ-dependent of relative change of $(R - R_{\perp})/(R_{//} - R_{\perp})$ in the resistance of the Sample I, II and III. The in-plane rotating magnetic field $H = 80$ Oe was selected.

maximum resistance determined by angle-dependent AMR measurement only indicates that the saturation magnetization is parallel to the direction of the current, not the easy axis [22]. Therefore, in our study, we considered carefully about the angular dependence of AMR measurement, and then found a new approach by analyzing of AMR results to determine the right direction of the easy axis. Given their simplicity, AMR measurement instruments can be easily set up. Our method provides an effective, convenient and low cost way of studying magnetic materials and devices, especially in deciding the magnetic easy axis.

2. Experimental

The samples were deposited via DC magnetron sputtering on 5 mm × 10 mm Si substrates at room temperature by using a $Ni_{80}Co_{20}$ target. In our study, we chose P-type and B-doped Si substrates to prepare samples, and covered Si with an SiO_2 layer. NiCo alloy is selected due to its large AMR value. The

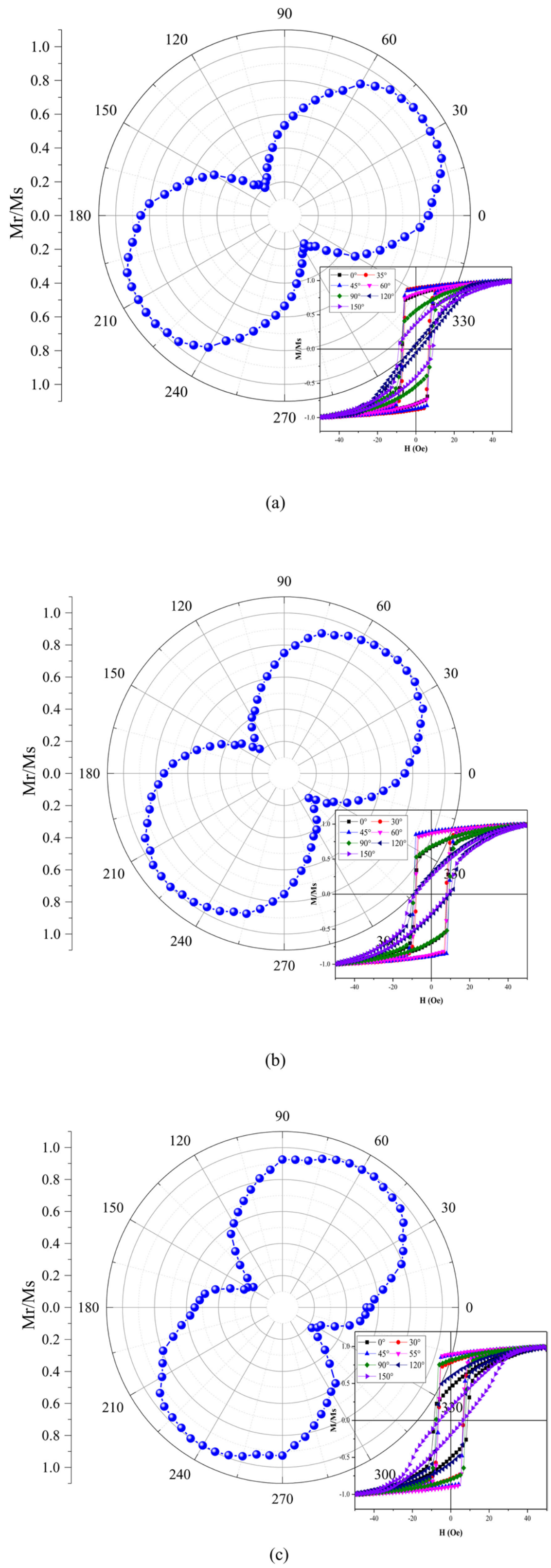

Figure 3. Angular dependence of the Mr/Ms for (a) Sample I, (b) Sample II, and (c) Sample III. The insets are magnetic hysteresis loops for typical angles.

nominal composition and thickness (in nm) of the samples were Si/SiO_2/Ta (5)/$Ni_{80}Co_{20}$ (60)/Ta (5). A constant magnetic field of 300 Oe was applied parallel to the film plane during

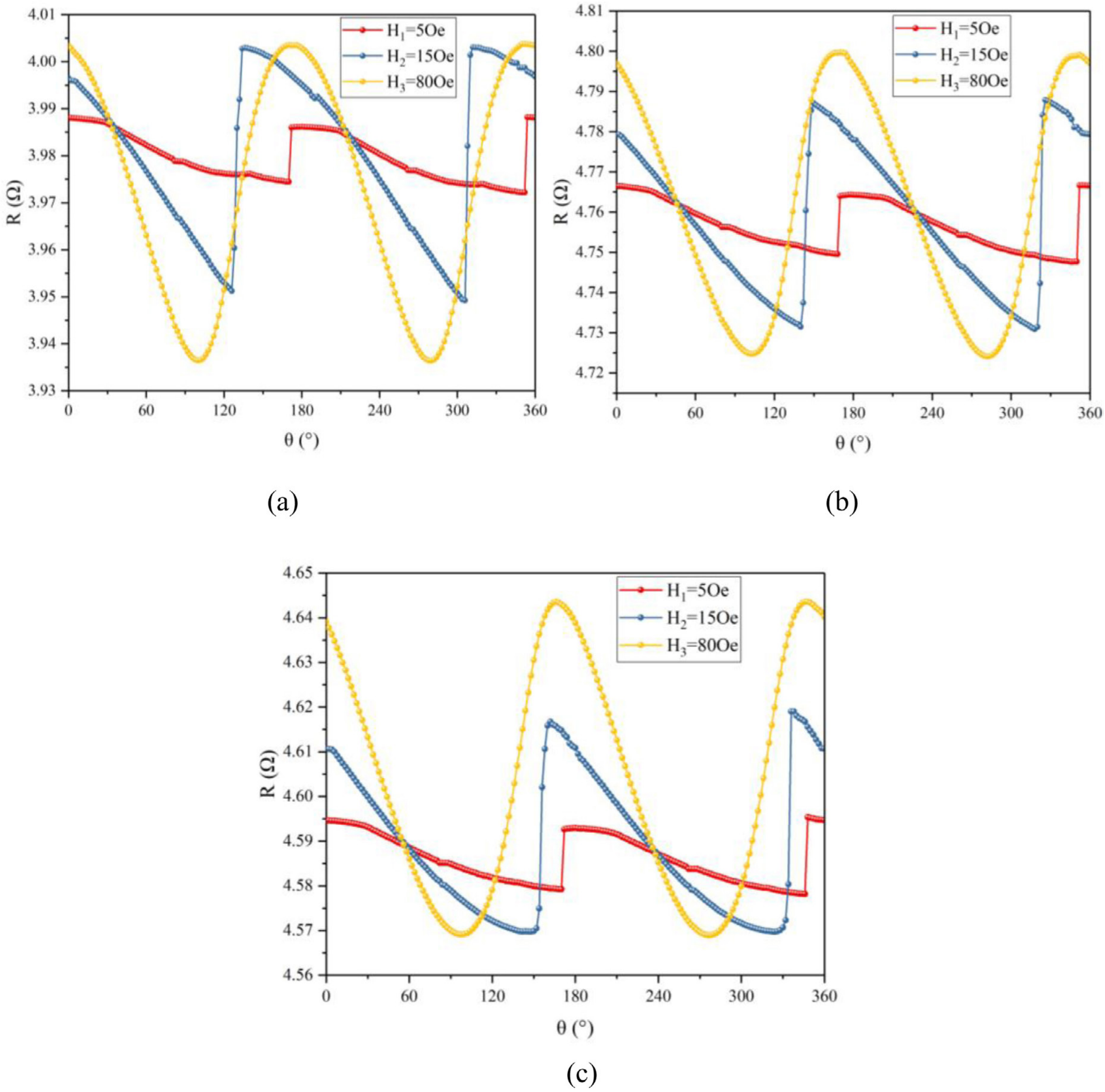

Figure 4. Angular dependence of AMR curves measured under the external fields of H_1, H_2, and H_3 for (a) Sample I, (b) Sample II, and (c) Sample III.

deposition to induce an easy axis along the magnetic field direction. For different samples, the constant magnetic field was applied at different angles (30°, 45° and 60°) to induce the easy axis along different directions. During deposition, the base vacuum was better than 8×10^{-6} Pa. The AMR measurements were performed by means of a standard four-probe configuration, as shown in figure 1. The DC current of 1 mA was supplied by a current source. During the angular dependence AMR measurement, the applied magnetic field H was fixed at a constant value and rotated to obtain the AMR curves. The direction of the current was fixed at the long axis of the substrate. The θ was defined as the angle between the directions of I and H. The magnetization measurements were performed in a BHV-525 vibrating sample magnetometer (VSM).

3. Results and discussion

In previous studies, the researchers confirmed the easy axis simply from the angle-dependence of AMR [19, 21]. They considered that the direction for achieving maximum resistance in angular dependent AMR measurement corresponds to the easy axis. In order to demonstrate this method to determine the easy axis is not accurate, and also to compare their measured results with our new approach, we first did the experiment as their way.

A set of samples of the film Ta (5 nm)/NiCo (60 nm)/Ta (5 nm) were prepared at different directions of the external magnetic field. The direction of the field can induce magnetic anisotropy, and the easy axis always orientates close to the

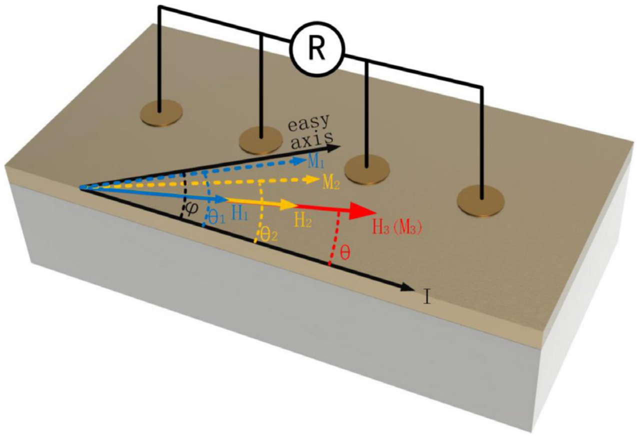

Figure 5. Schematic for analyzing the testing results.

external field. The three typical directions of the external field were selected along 30°, 45° and 60°, which we defined as Sample I, II and III, respectively.

As shown in figure 2, the angle θ-dependent AMR measurements for Sample I, II and III were carried out by rotating an external H within the plane of the layers. To guarantee an accurate measurement, the sample should stay still within the gap of the coils, and a couple of orthogonal coils can be driven in quadrature to achieve a rotating magnetic field with constant intensity. During the measurements, two maximum MR peaks are observed. The maximum MR peaks for Sample I to III are almost the same and near 170° and 350°. If these angles are considered as the directions of the easy axes, then they are inconsistent with the initial deposition magnetic field.

To verify the easy axis of these three samples, the angle-dependent magnetic hysteresis loops were tested via VSM. The easy axes of these samples were roughly determined by comparing the remnant magnetization Mr.

As shown in figure 3, the samples display a uniaxial magnetic anisotropy, and their easy axes are near 35°, 45° and 55°. These values of angle are close to the induced magnetic field direction. The small angle deviation from the induced field may be resulted in the film deposition process and impact by the structure of the film itself. It demonstrates that the magnetic easy axis cannot be determined simply from the maximum value recorded in the angular dependence of AMR measurement [19].

In this paper, we report a new approach to determine the direction of the easy axis also by angular dependence of AMR measurement. The correct easy axis can be determined by selecting three different magnitudes of applied external fields and analyzing the AMR measurement results. Choosing three suitable rotating magnetic fields H during the AMR measurements is critical in our method. The first rotating magnetic field H_1 should be lower than the coercivity H_c. In our study, we selected H_1 to be approximately half of the H_c. Under this condition, the direction of magnetic moments lags to the in-plane rotating magnetic field. The magnitude of the second rotating magnetic field H_2 was selected to be larger than H_1 and smaller than the saturated field of the film. In other words, the second rotating magnetic field is a medium field. The third

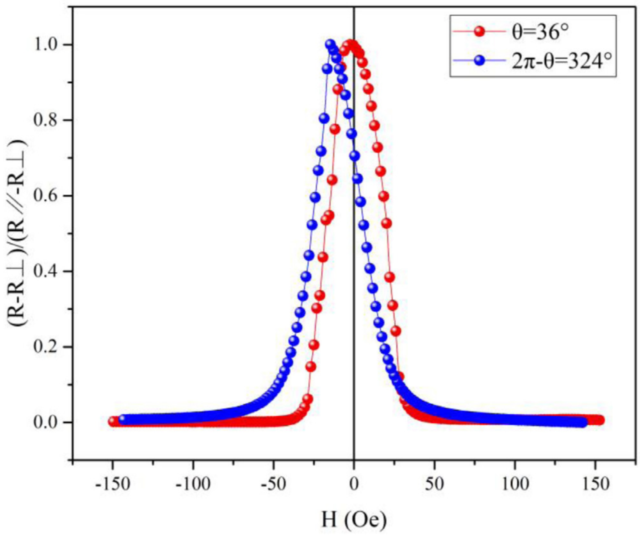

Figure 6. AMR curves of the Sample I measured along the calculated easy axis direction $\theta = 36°$ and $2\pi - \theta = 324°$.

Table 1. Comparison of direction of easy axis achieving by different methods.

	Our method (°)	VSM method (°)	Calculation method (°)
Sample I	35	35	36
Sample II	46	45	45
Sample III	56	55	56

rotating magnetic field H_3 must be large enough to saturate the magnetization and for the magnetic moments to follow the direction of H_3.

Figure 4 shows the angle-dependent AMR curves for Sample I, II and III that are measured under the rotating fields of 5, 15 and 80 Oe. In the draft of each AMR curve, two intersections for three different measured fields can be achieved. The angle corresponding to the intersection is treated as the direction of the easy axis. The reason is demonstrated in the following. In the discussion, we initially assume that the moments are coherent rotation. As shown in figure 5, if the easy axis is located at angle φ and if the rotating field is located at angle θ at a certain period, then the directions of the moments are different for applied the three different fields.

When we need to determine the three different fields, we can know H_{sat} from the AMR curves of the sample such as figure 6. Given that, since H_1 should be lower than H_c and that H_3 should be large enough to saturate the magnetization, then the H_3 can be selected to be much larger than H_{sat}, H_2 can be selected slightly lower than the H_{sat} and H_1 can be selected to be only several Oe. When H_1 is applied, its magnitude is too small to orient the moments to the direction of the external field. Therefore, these moments lie along θ_1. When H_2 is applied, its magnitude is also lower than the saturated field, thereby preventing the moments from being oriented to the direction of H_2. However, given that H_2 is larger than H_1, the moments are oriented along θ_2. When the largest field H_3 is applied, the moments will lie along the direction of the external field at angle θ. According to the definition of AMR, the anisotropic change of resistance R can be expressed as [23]:

$$R = R_{\perp} + \Delta R\cos^2\theta. \tag{1}$$

With $\Delta R = (R_{//} - R_{\perp})$ and $R_{\perp}$ $(R_{//})$ being the resistance with current perpendicular (parallel) to the magnetization.

Given that $\theta_1 > \theta_2 > \theta$, these three different fields have three different resistance values applied at the same angle θ. The same value of resistance can only be obtained when three different magnitudes of fields are applied along the easy axis. In other words, the resistance values $R(H_1) = R(H_2) = R(H_3)$ because of $\theta_1 = \theta_2 = \theta$. At interaction, the resistance values are the same. Therefore, it is corresponding to the easy axis. By using this method, the easy axes for Sample I, II and III are 35°, 46° and 56°, which agreed very well with the VSM results presented in figure 3.

Meanwhile, the magnetic moments of the magnetic film usually lie along the easy axis without an external magnetic field. To further confirm the angle of the easy axis which is decided by our method, we can use equation (1) to calculate the θ when $H = 0$. In the calculation, the R $(H = 0)$ was obtained without the external field, and the testing current was also applied along the long axis. ΔR was calculated from figure 4. In the curves achieved at the saturated range ($H = 80$ Oe), the maximum (minimum) value corresponded to $R_{//}$ $(R_{\perp})$. Therefore, two angles, namely, θ and $2\pi - \theta$,were calculated out. One of these angles is the real angle for the easy axis, whereas the other angle should be excluded. To exclude the incorrect value, normal sweeping field AMR measurements, which current I is perpendicular to the external field, were performed. The direction of the current was along the calculating easy axis (θ or $2\pi - \theta$). The AMR curves of $(R - R_{\perp})/(R_{//} - R_{\perp})$ with Sample I as the example are presented in figure 6.

If the MR curve is fully symmetric and reaches its maximum at $H = 0$, then the direction of this angle can represent the direction of the easy axis, and the other angle can be excluded. The easy axis determined by our new approach is compared with the axes determined by two other traditional approaches in table 1.

It is obviously that the easy axis achieved by the intersections in AMR angular measurements is almost the same as other traditional approaches. It demonstrates that the method proposed in our study is an efficient and feasible way to decide the easy axis, and the error of the angle determined by our approaches is within 2°. It can support studies on many magnetic materials, and reduce the demand of complicated equipment.

4. Conclusions

We develop an approach that determines the easy axis by using angle-dependent AMR measurements. This approach can easily and effectively determine the easy axis compared with normal magnetic hysteresis loop measurements and other methods based on the AMR effect. This method can be used in researching numerous of magnetic material with less demands of the complicated equipment.

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ORCID iDs

Xiaoli Tang https://orcid.org/0000-0002-9477-3375
Hua Su https://orcid.org/0000-0002-6951-9252

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