Sains Malaysiana 41(5)(2012): 617–621

Longitudinal and Polar MOKE Magnetometry of Magnetoresistive Cobalt Thin Films Prepared by Thermal Evaporation

(Magnetometri Longitudal dan Kutub MOKE Filem Nipis Kobalt Magnetorintangan yang disediakan Melalui Penyejatan Terma)

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ABSTRACT

Cobalt films of thickness 21, 29 and 68 nm were prepared by thermal evaporation with a deposition rate around 0.3 nm/s. Their hysteresis loops from longitudinal and polar magneto-optic Kerr effect (MOKE) magnetometry differed from typical characteristics of uniaxial magnetic anisotropy but still indicated the preference of in-plane anisotropy over perpendicular anisotropy. The longitudinal hysteresis loop of the 68 nm-thick film was decidedly in a transcritical state signified by an enhanced coercive field. Changing the angle (θ) between the 2500 Oe-magnetic field and the current gave rise to the change in electrical resistance (R_θ) of 29 nm-thick film and the plot between R_θ and $\cos^2\theta$ could be linearly fitted. The changes in resistance due to this anisotropic magnetoresistance (AMR) effect ranged from -0.08 % ($\theta = 90^o$) to +0.04 % ($\theta = 0^o$).

Keywords: Anisotropic magnetoresistance; ferromagnetic thin film; hysteresis loop; magneto-optic Kerr effect; thermal evaporation

ABSTRAK

Filem kobalt dengan ketebalan 21, 29 dan 68 nm telah disediakan melalui penyejatan terma dengan kadar pemendapan 0.3nm/s. Gelung histerisis daripada magnetometri longitudal dan kesan magneto-optik Kerr adalah berbeza daripada ciri-ciri biasa anisotrop magnet ekapaksi tetapi masih menunjukkan kecenderungnan kepada anisotrop dalam-satah berbanding anisotrop serenjang. Gelung histerisis longitudal filem dengan ketebalan 68 nm jelas dalam keadaan transkritikal dan ditandakan oleh medan paksaan yang meningkat. Mengubah sudut (θ) antara medan magnet 2500 Oe dan arus telah mengubah rintangan elektrik (R_θ) filem dengan ketebalan 29 nm dan plot antara R_θ dan $\cos^2\theta$ boleh disuaikan secara linear. Perubahan dalam rintangan disebabkan oleh magnetorintangan tak isotropik (AMR) ini adalah daripada -0.08% ($\theta=90^o$) ke +0.04 % ($\theta= 0^o$).

Kata kunci: Filem nipis feromagnet; gelung histerisis; kesan magneto-optik Kerr; magnetorintangan anisotropik; penyejatan terma

INTRODUCTION

Thin ferromagnetic films (e.g. iron, nickel, cobalt and μ-metal) are important parts in electromechanical systems, data storage and sensing devices (O' Handley 2000). Some of these applications are based on the magnetoresistance (MR) effect which is a change in electrical resistance when materials are subjected to the external magnetic field. There are several types of MR classified by their origin. Anisotropic magnetoresistance (AMR) arises from spin-orbit interactions resulting in the dependence of scattering rates of conduction electrons on local magnetization in ferromagnetic materials (Gil et al. 2005; Rhee & Kim 2001; Yi et al. 2004). The AMR effect is proportional to $\cos^2\theta$ where θ is an angle between electrical current and magnetization direction (O' Handley 2000).

To study the magnetization process of magnetic materials, hysteresis loops can be traced by magnetometers. Among available magnetometers, Magneto-Optic Kerr Effect (MOKE) magnetometers are often used in the case of thin films. Based on the principle of Kerr rotation (Allwood et al. 2010), the polarization of the reflected light wave from a ferromagnetic layer is rotated and dependent on its magnetization orientation. A hysteresis loop is a plot of this magnetization as a function of the varying magnetic field applied to the film. Whereas other magnetometers measure average magnetic flux density of bulk samples, MOKE can be used to study local magnetism. Different configurations, i.e. polar (out-of-plane), transverse and longitudinal, of MOKE vector magnetometry have been employed to investigate the variation of magnetic properties of thin films from different fabrication techniques. Examples include the studies of magnetization reversal process of epitaxial iron films on gallium arsenide substrates (Daboo et al. 1995) and dynamic hysteresis of iron between 0.03 and 3000 Hz (Moore & Bland 2004). For other ferromagnets, magnetic anisotropy of sputtered μ-metal films were studied by using both polar and traverse MOKE

(Svalov et al. 2004) whereas the polar hysteresis loops of nickel films were dependent on their conditions in the electrodeposition (Vasilache et al. 2010).

Compared to other ferromagnetic materials, cobalt has a high magnetic anisotropy and cobalt/copper multilayers are widely implemented as giant magnetoresistive materials (Ying & Khuan 2008). Magnetic properties of electrodeposited cobalt films on copper substrates were studied by MOKE magnetometry in both thick (Bhuiyan et al. 2008) and ultrathin (Mangen et al. 2010) regimes. Ultrathin cobalt was also grown by electron-beam evaporation and its hysteresis loop was modified by the addition of a copper overlayer (Chan et al. 2007). With a different substrate, the formation of cobalt disilicide between the cobalt film and the silicon substrate and its effect on magnetic properties were revealed by MOKE spectra (Agarwal et al. 2006). Compared to electron-beam evaporation, thermal evaporation is regarded as a low-cost alternative for growing thin films on silicon substrates (Abd Rahim et al. 2011). In this work, AMR of thermally evaporated cobalt films were measured and related to their longitudinal and polar MOKE hysteresis loops.

Materials and Methods

Cobalt films on silicon substrates were prepared by the thermal evaporation technique. With a pressure inside the evaporator of 10^{-4} torr, pieces of cobalt (0.05 g) in a heat resistance-tungsten boat were melted and then evaporated (boiling point 2,870 ºC) by a current up to 50 A. A silicon substrate was installed above the evaporation boat and covered by a shutter. The time of cobalt deposition on the silicon substrate was varied by the shutter control as 80, 90 and 240 seconds leading to three different film thicknesses. In the thickness measurement by the stylus-method profiometry, each cobalt film was partly etched to create a step between the film and the substrate. A stylus traced the topography of the film-substrate step and its mechanical movement was measured. Ten repeated measurements were performed on each sample to obtain average thickness.

In the hysteresis measurement by a MOKE magnetometer (Rattanasuporn et al. 2008), cobalt films on silicon substrates of length 20 mm and width 10 mm were installed in the gap of a C-shape electromagnet with sweeping magnetic field between -2000 and 2000 Oe. A beam of He-Ne laser (wavelength 633 nm) through a polarizer was incident on the area around 3 mm^2 of each magnetizing cobalt film. The reflected beam passed through the other polarizer before reaching a photodiode detector. The second polarizer, acting as an analyzer of polarization, was aligned at the angle θ with respect to the first polarizer. This alignment of the polarizers enabled the detection of the Kerr rotation at the silicon photodiode. A reference photodiode, closed to the one analyzed the reflected beam, measured the intensity of background light. In order to reduce the background, the light was shielded around the detectors. In the set-up with the beam intensity transmitted from the first polarizer I_{in}, a variation of the reflected beam intensity (ΔI_{out}) is proportional to the Kerr rotation ($\Delta\theta$) and magnetization (M):

$$\Delta I_{out} = -I_{in}\sin(2\theta)\Delta\theta = -I_{in}\sin(2\theta)KM, \quad (1)$$

where K is a constant. Hysteresis loops can then be expressed in terms of the magnetization normalized to the saturation magnetization (M/M_s) as a function of magnetizing field. Five repeated measurements were performed in longitudinal and polar configurations. In the longitudinal configuration the magnetic field is applied parallel to the film surface and parallel to the plane of light incidence whereas the out-of-plane magnetic field is parallel to the light incidence plane in the polar MOKE. The coercive field is determined from an x-intercept of the loop and the squareness is a ratio of the remanent magnetization obtained from a y-intercept of the loop to the saturation magnetization.

In the four-point probe MR measurements, a piece of 9×18 mm^2 sample was sliced from a cobalt-coated silicon substrate. The sample was attached to a sample holder with contacts by four pins. The in-line arrangement of these four pins eliminated the detection of the Hall effect (Epshtein et al. 2003). A current source (Keithley 220) forced a constant in-plane current of 0.1 mA through a pair of outer pins and a nanovoltmeter (Agilent 34420A) measured the voltage drop across the two inner pins. The sample holder was installed in an electromagnet whose field was either in-plane or perpendicular to the current flow. A computer-controlled power supply continuously swept magnetic field at a rate of 36 Oe/s up to 2000 Oe. The electrical resistance (R) was then deduced and plotted as a function of magnetic field. The MR ratio is defined as $(R - R_0)/ R_0$, where R_0 is zero-field resistance. The results were compared to the MR when the field was parallel to the current. To compare experimental results with the theory (O' Handley 2000), the other measurement recorded the resistance in a fixed 2500 Oe-magnetic field (R_θ) as a function of the angle between current and magnetic field (θ) by rotating the electromagnet 15 degrees at a time.

Results and Discussion

From the thickness measurements by stylus method profiometry, the average film thickness are 21, 29 and 68 nm for the depositions of 80, 90 and 240 s corresponding to a cobalt deposition rate of approximately 0.3 nm/s. The roughness tends to increase in thicker films as quantified by the standard deviation of repeated measurements in Table 1. Longitudinal and polar hysteresis loops of cobalt films, respectively shown in Figure 1 and 2, are clearly different. Both loops exhibit deviations from the ideal case of uniaxial magnetic anisotropy (O' Handley 2000). Nevertheless, the preference of the in-plane anisotropy is apparent because the films are much easier to magnetize with lower saturation fields in the longitudinal configuration. Detailed magnetic parameters obtained from the hysteresis loops are listed in Table 1. From the longitudinal MOKE measurement, the

29 nm-thick film has the minimum coercive field of 55.5 Oe and a saturation field around 132.6 Oe reflecting its soft magnetic characteristics. Moreover, it also has the highest squareness of 0.94 and intensity of the reflected light corresponding to the highest saturation magnetization. While the 21 nm-thick film has comparable magnetic properties to those of the 29 nm-thick film, the longitudinal hysteresis loop in the case of 68 nm is clearly distinguished by its enhanced coercive and saturation fields and its squareness is significantly reduced to 0.49. This loop resembles those in the transcritical state which occurs in thicker films whose magnetization is not entirely oriented in-plane due to the presence of perpendicular anisotropy (Svalov et al. 2004). By applying magnetic field in the polar MOKE measurement, the saturation field of 29 nm and 68 nm-thick films exceeds 1700 Oe without coherent rotations. Other magnetic parameters of both thickness become comparable with the coercive field above 200 Oe and the squareness as low as 0.12.

Because the MOKE results indicate the in-plane anisotropy, magnetic field is applied in-plane of the 29 nm-thick film in the MR measurements. It was reported

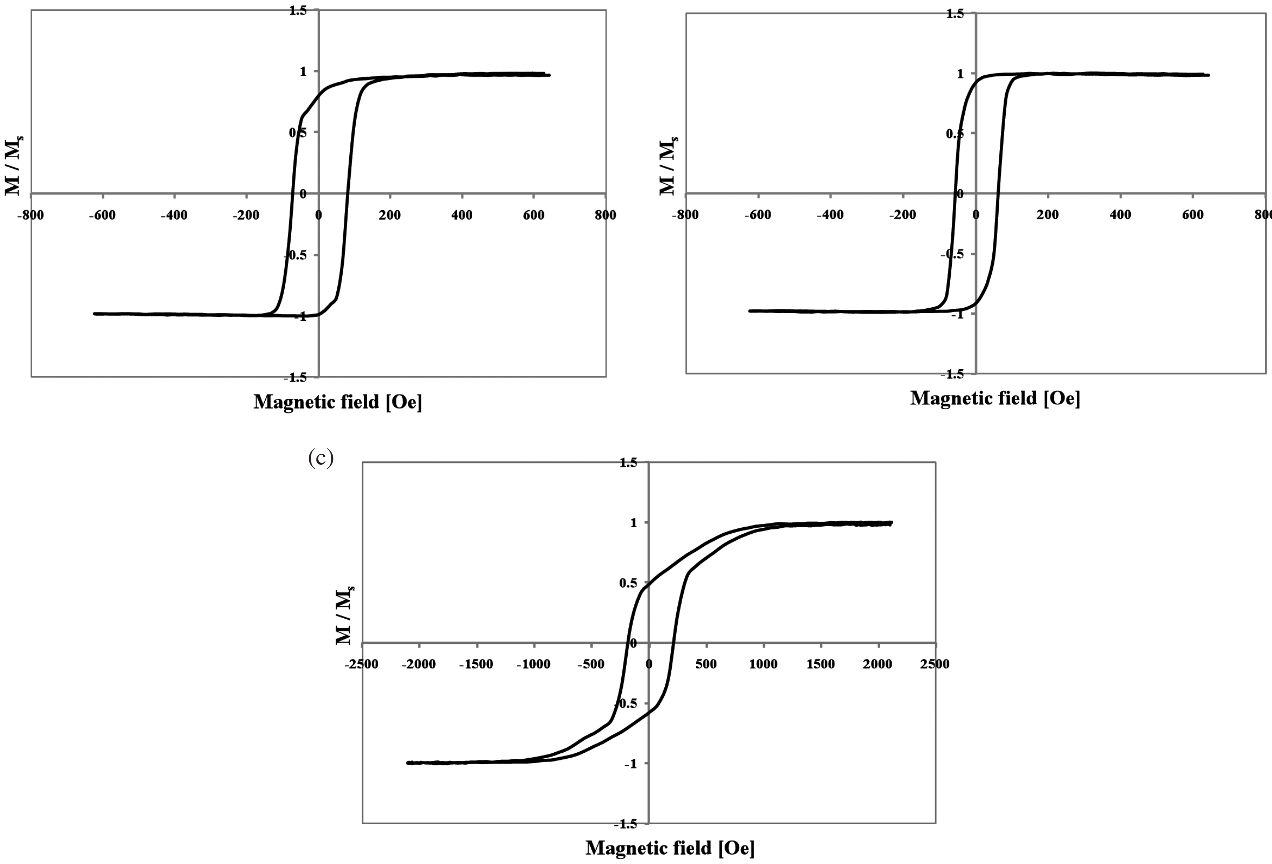

FIGURE 1. Longitudinal hysteresis loops of (a) 21, (b) 29 and (c) 68 nm-thick cobalt films.

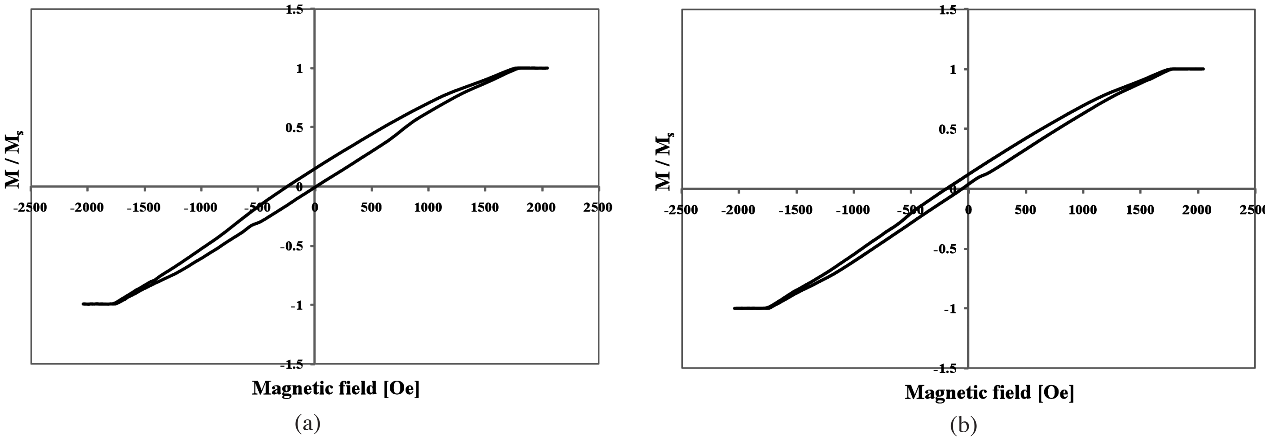

FIGURE 2. Polar hysteresis loops of (a) 29 and (b) 68 nm-thick cobalt films

that applications of out-of-plane field led to a larger MR effect in polycrystalline cobalt and nickel films (Gil et al. 2005; Rhee & Kim 2001) but the increased saturation field reduces its potential application in sensing and data storage. Figure 3 compares MR curves of the 29 nm-thick cobalt film on silicon substrate performed at different magnetic field angles (θ). In a perpendicular configuration ($\theta = 90^o$), the film exhibits a decrease in resistance corresponding to a magnetization reversal process which approaches saturation from 1500 Oe. By adjusting θ to 0, 15, 30, 45, 60 and 75 degrees, the resistance also changes in the magnetic field but with different MR ratios. The MR ratio ranges from -0.08 % (perpendicular configuration, $\theta = 90^o$) to +0.04 % (parallel configuration, $\theta = 0^o$). Due to the AMR effect, the resistance of the film in 2500 Oe-magnetic field (R_θ) is dependent on the magnetic field angle (θ). As seen in Figure 4, the plot of $\cos^2\theta$ against R_θ can be linearly fitted. It follows that the measurement of resistance at various angles agrees with the theory of AMR (O' Handley 2000). However, data points in Figure 4 shows some deviations from the trend line due to the susceptibility of resistance to Joule heating and temperature drift. This effect is increasingly significant in Figure 3 as seen in the case of 30°-75° because longer measurement times are required for the magnetic field sweep.

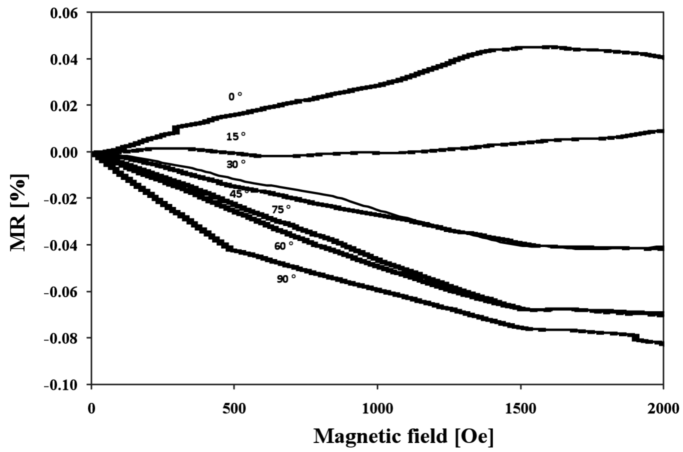

FIGURE 3. MR curves of a 29 nm-thick cobalt film of varying angles between current and applied magnetic field

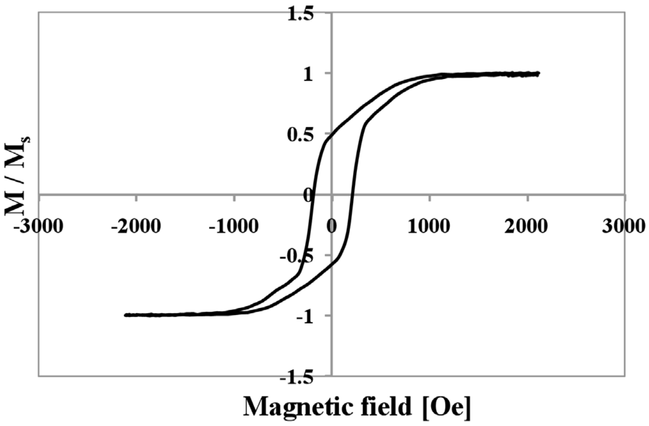

FIGURE 4. Resistance of a 29 nm-thick cobalt film as a function of cosθ squared where θ is an angle between current and applied mangnetic field

TABLE 1. Magnetic properties of evaporated cobalt films of varying thickness obtained from longitudinal and polar MOKE magnetometry

Deposition time (s)	Film thickness (nm)	Longitudinal MOKE			Polar MOKE		
		Coercive field (Oe)	Squareness	Saturation field (Oe)	Coercive field (Oe)	Squareness	Saturation field (Oe)
80	21±4	71.5	0.83	165.3	-	-	-
90	29±5	55.5	0.94	132.6	243.2	0.15	1765.2
240	68±5	161.8	0.49	1123.9	202.5	0.12	1744.0

Conclusion

Longitudinal and polar MOKE configurations are successfully implemented in tracing hysteresis loops of 21, 29 and 68 nm-thick evaporated cobalt films. The films tend to have in-plane anisotropy but the transcritical state is also observed in the thickest film. The 29 nm-thick film exhibits AMR with +0.04% increase and -0.08% decrease when the current is parallel and perpendicular to the magnetic field, respectively. Its resistance in a 2500 Oe-magnetic field was proportional to $\cos^2\theta$ as predicted by theory.

Acknowledgement

This work was funded by Walailak University Research Grant. We would like to thank the National Metals and Materials Technology Center (MTEC) for the thickness measurement.

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Received: 3 August 2011
Accepted: 27 October 2011