Anisotropic Magnetoresistance of Cobalt Films Prepared by Thermal Evaporation

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ABSTRACT

Cobalt films on silicon substrates were prepared by thermal evaporation. By evaporating 0.05 g of cobalt for 80-240 s, a thickness from 21.1 to 67.7 nm was obtained with a deposition rate about 0.26-0.32 nm per second. The 29 nm-thick cobalt film exhibited magnetoresistance (MR) ranging from -0.0793% (field perpendicular to the current) to +0.0134% (field parallel to the current) with saturation in a 220 mT magnetic field. This MR was attributed to anisotropic magnetoresistance (AMR) since changing the angle between the field and the current (θ) gave rise to a change in the electrical resistance (R_θ). The results agreed with the theory since the plot between R_θ and $\cos^2\theta$ could be linearly fitted. AMR was not observed in non-ferromagnetic gold films whose resistance was insensitive to the angle between the current and magnetic field.

Key words: Magnetoresistance - AMR - Thermal evaporation - Thin films

INTRODUCTION

Ferromagnetic thin films (e.g. Co, Ni, Fe, NiFe) are widely implemented in sensors and computer hard disks because of their anisotropic magnetoresistance (AMR). AMR is a change of electrical resistance when a ferromagnet is subjected to an external magnetic field. Unlike giant magnetoresistance (GMR) (1) and magnetoresistance due to the Lorentz force (2), AMR is observed exclusively in ferromagnetic materials due to spin-orbit interactions. Since there are a lot of holes in the magnetization direction, conduction electrons are therefore easily trapped in this direction (3). As a result, the resistance is largest when the current is parallel to the magnetic field. Although the theory is somewhat complicated, AMR is easily observed by its angle-dependent characteristics. When the magnetic field is parallel to the current, the resistance increases with magnetic field. On the other hand, the resistance drops when the increasing magnetic field is perpendicular to the current. McGuire and Potter proposed an equation describing angle dependent resistance as $R_\theta = R_\perp + (R_{//} - R_\perp)\cos^2\theta$ where $R_{//}$, $R_\perp$ and R_θ are saturation resistance when the current is 0, 90 and θ degree relative to the magnetic field respectively (4). Although AMR was discovered more than a century ago by William Thomson, it was not until 1950s that it was fully explained and began to be widely implemented in magnetic read heads and sensors. Until now, research on AMR remains active and much interest has extended to nanostructures whose dimensions regulate its magnetic properties (5,6). For example, it was found that thickness of cobalt films determined arrangement of magnetic domains and this clearly influenced the magnetoresistance (MR). AMR is also present in spin valves and GMR devices (7,8). In this paper, cobalt films were fabricated by thermal evaporation and studied. In thermal evaporation, metals are heated by high electrical currents, become vapour and deposit on a substrate. As a control, experiment on a non-ferromagnetic gold film was also performed.

MATERIALS AND METHODS

Cobalt films were prepared in a thermal evaporator shown in **Figure 1**. Inside a glass bell jar were heat resistance-tungsten boats connected to high current electrodes and a substrate holder covered by a shutter. Small pieces of cobalt were cleaned in an ultrasonic bath and put on the tungsten boat. After rotary and diffusion pumps reduced pressure inside the bell jar down to 10^{-4} torr, the power supply ramped the current up to 50 A, until the boat glowed red hot and the cobalt melted, then evaporated (boiling point 2,870ºC). To allow cobalt deposition on a substrate, the shutter was removed. Two types of substrate, glass and silicon, were used. To obtain different film thickness, cobalt mass was varied from 0.05 g to 0.12 g and evaporation time was varied from 80 s to 240 s. Cobalt films were characterized by scanning electron microscopy (SEM) and stylus-method profilometry. Before the thickness measurement by the stylus-method profilometry, samples were 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 an average thickness.

A piece of 9×18 mm^2 sample was sliced from a cobalt-coated silicon wafer to use in four-point probe MR measurements. The sample was attached to a sample holder with four pins making contacts to the cobalt film. 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 in-plane and perpendicular to the current flow. A computer-controlled power supply continuously swept the magnetic field at a rate of 3.6 mT/s up to 220 mT. The resistance was then deduced and plotted as a function of the magnetic field. Measurements were repeated as the electromagnet was rotated 15 degrees at a time until the field was parallel to the current. To test the theory proposed by McGuire and Potter (4), a different measurement was performed by recording the resistance (R_θ) in a fixed magnetic field of 250 mT as a function of the angle between the current and magnetic field (θ).

RESULTS AND DISCUSSION

Film Characterization

As a preliminary experiment, cobalt film was first deposited on a glass substrate. The top view micrograph in **Figure 2** shows a rough film surface. The SEM micrograph taken from the side view reveals the cobalt thickness of 300 nm on this glass substrate. More experiments confirmed that excessive deposition affected the quality of the cobalt films. By using large masses for long deposition times, the films peeled off easily. The proper conditions are a mass less than 0.10 g and a deposition time less than 240 s. These conditions were subsequently implemented in the preparation of cobalt films on silicon substrates. **Figure 3** shows the top view of a smooth cobalt film on silicon substrates taken by SEM. However, the thickness of this film could not be obtained from SEM and was measured by stylus method profilometry. An example of the profile is shown in **Figure 4**. By using 0.05 g of cobalt, the film thicknesses are 21.1, 29.4 and 67.7 nm for 80, 90 and 240 s depositions corresponding to a cobalt deposition rate of 0.26 - 0.32 nm/s.

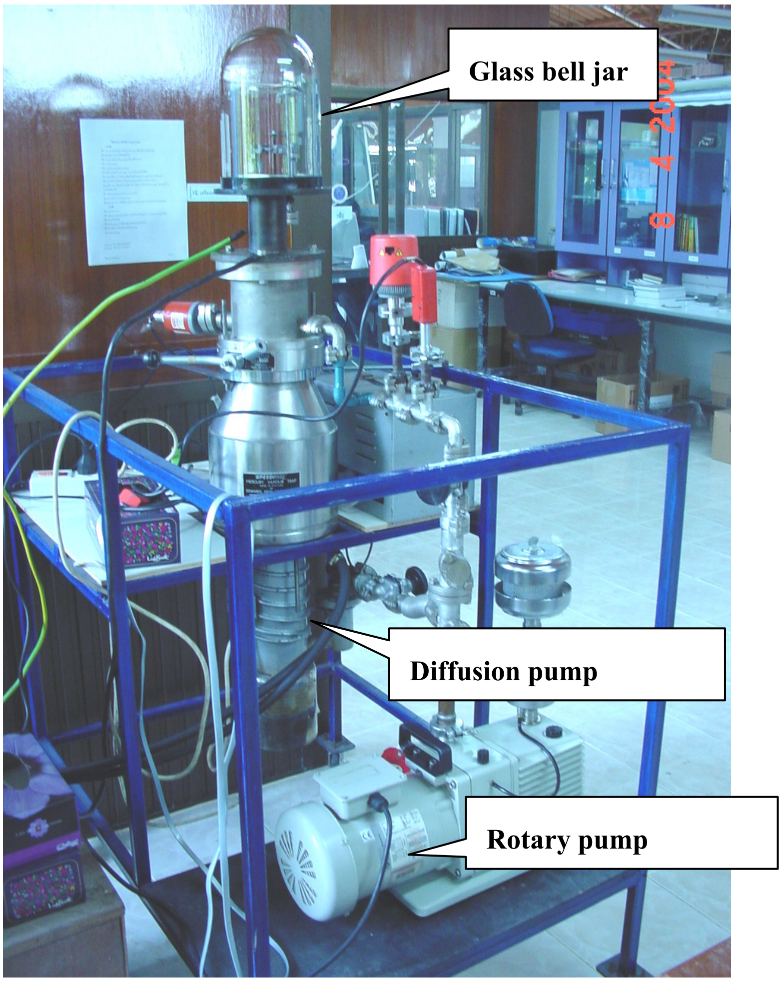

Figure 1. Thermal evaporator consisting of vacuum bell jar, pumps and gauges.

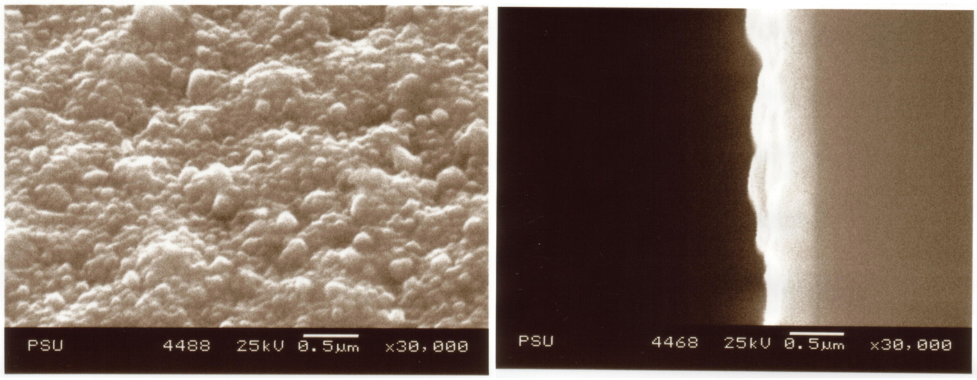

Figure 2. Top view (left) and side view (right) of cobalt film on glass substrate obtained by SEM (× 30,000).

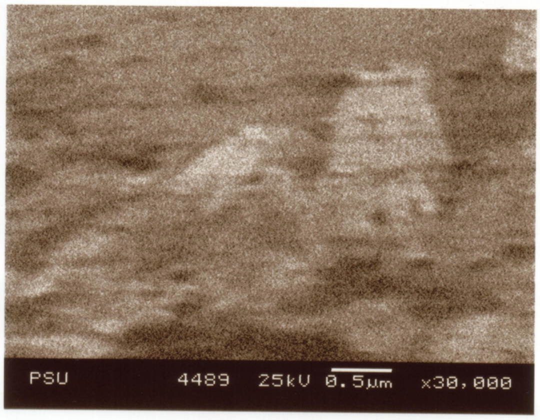

Figure 3. Top view of cobalt film on silicon substrate obtained by SEM (× 30,000).

Figure 4. Thickness of a cobalt film indicated by stylus method profilometry.

Magnetoresistance Measurement

In our measurements, the magnetic field is applied along the plane of samples because in-plane magnetization is expected. According to previous studies (9,10), applications of out-of-plane field leads to larger MR and saturation field. The latter reduces potential applications in sensing and data storage. **Figure 5** compares MR curves of 29.4 nm cobalt film on silicon substrate performed at different magnetic field angles (θ). In a perpendicular configuration (θ = 90º), the film exhibits a decrease in resistance corresponding to a magnetization reversal process. Under 220 mT, the resistance reaches the saturation as the film is completely magnetized. The relatively high saturation field is attributable to the multi-domain nature of the film (5). By adjusting θ to 0, 15, 30, 45, 60 and 75 degrees, the resistance also changes in magnetic field but with different MR magnitudes. The magnitude of MR, defined as $[R_\theta - R_0]/R_0$, where R_0 is zero-field resistance, ranges from -0.0793% (perpendicular configuration, θ = 90º) to +0.0134% (parallel configuration, θ = 0º). In **Figure 6**, the resistance in magnetic field (R_θ) is dependent on the magnetic field angle (θ) because of AMR in the cobalt film. Measurements of resistance at various angles agree with the equation proposed by McGuire and Potter (4). As seen in **Figure 6**, the plot of $\cos^2\theta$ against R_θ is linearly fitted. A slight deviation from the theory is explained by the susceptibility of resistance to Joule heating and room temperature fluctuation. Measurements on samples of different thickness indicate that AMR is clearly not observed in thicker samples. This relates to the roughness of the films resulting in substantial noise. Multi-domain arrangements in thicker films also reduce AMR. In addition to the thickness, the width and the length of cobalt samples affect its MR since they determine how the domains are arranged. From experiments, AMR is clearly observed in samples with high length-to-width ratio. According to Chang (11), ferromagnetic films may also process planar Hall effect. However, with our four pins in-line measurement configuration, the planar Hall effect and the ordinary Hall effect are not observable. In order to study the Hall effect, a current-across-voltage geometry must be arranged.

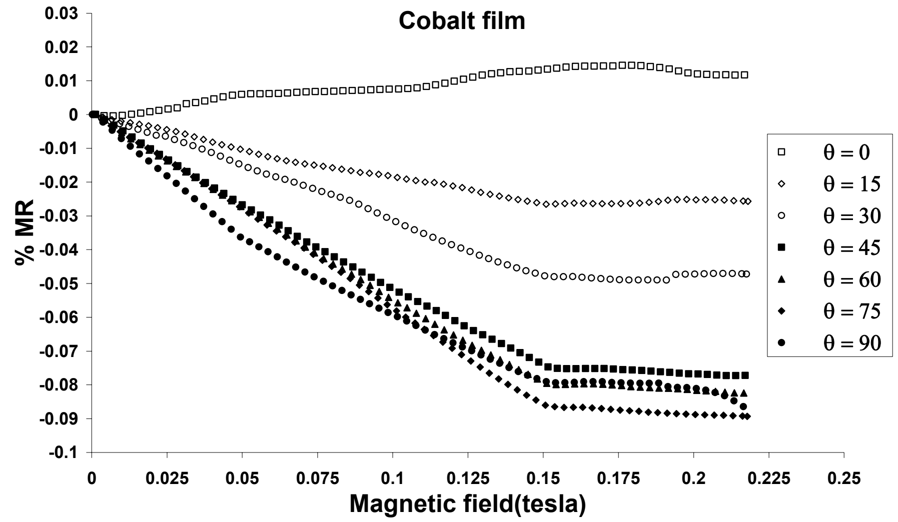

Figure 5. MR curves of cobalt film compared at various angles between current and magnetic field.

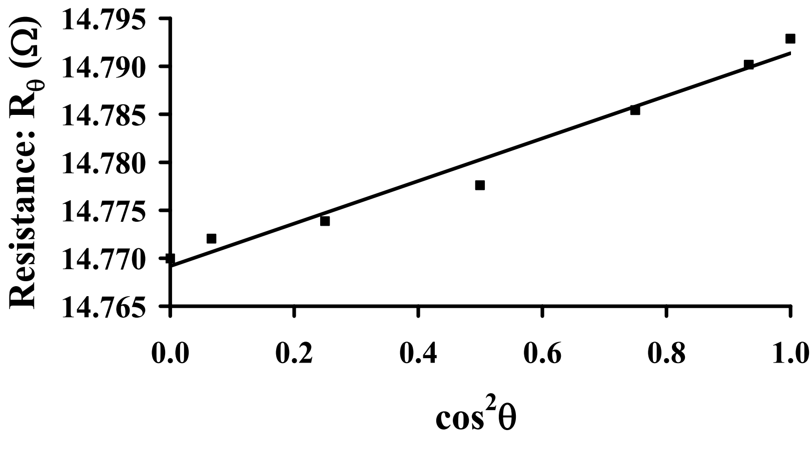

Figure 6. Resistance of a cobalt film plotted against $\cos^2\theta$.

Application as an Angular Sensor

A simple angular sensor was developed by attaching 2 permanent magnets on a rotating plate as shown in **Figure 7**. These magnets produce magnetic field about 110 mT in the gap. A cobalt film was put in the gap and its resistance is monitored by a computer-interfaced nanovoltmeter. When the plate is rotated, the resistance changes according to the angle of rotation as seen in **Figure 8**. By turning the magnetic field by 90 degrees, the resistance changes by 1.15%. With proper calibration, the resistance may convert into angle. However, thermal drift has to be taken into account to obtain a precise angle measurement and repeatability. Furthermore, the AMR sensor is nonlinear because the resistance is $\cos^2\theta$ dependent. Finally, to confirm that the effect is purely magnetic, a 100 nm-thick gold film replaces the cobalt film prepared by evaporation. By turning the magnetic field by 90 degrees, the resistance is not sensitive to the field direction as shown in **Figure 9**. The angle-independent resistance can be well explained since non-ferromagnetic gold should process no AMR.

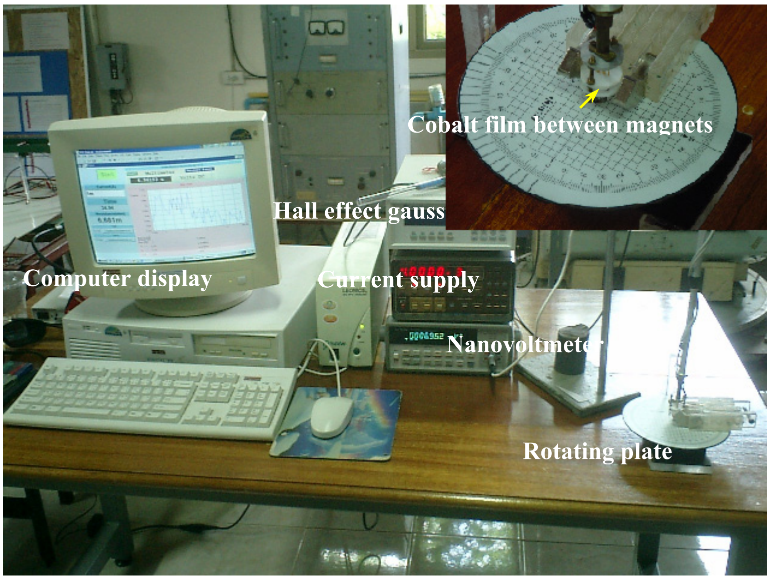

Figure 7. Angular sensor system consisting of a rotating plate, a current supply and a computer interfaced nanovoltmeter.

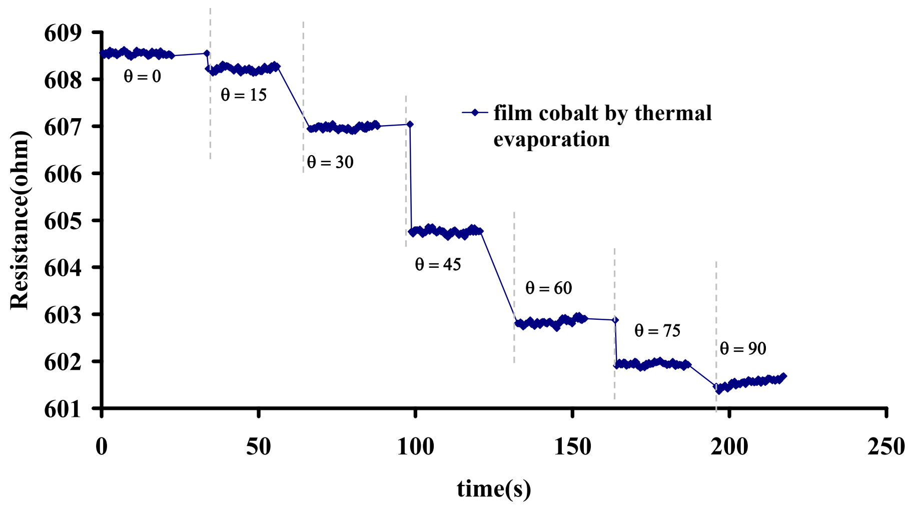

Figure 8. Change in resistance of cobalt film as the magnetic field is turned 15 degrees at a time relative to the current.

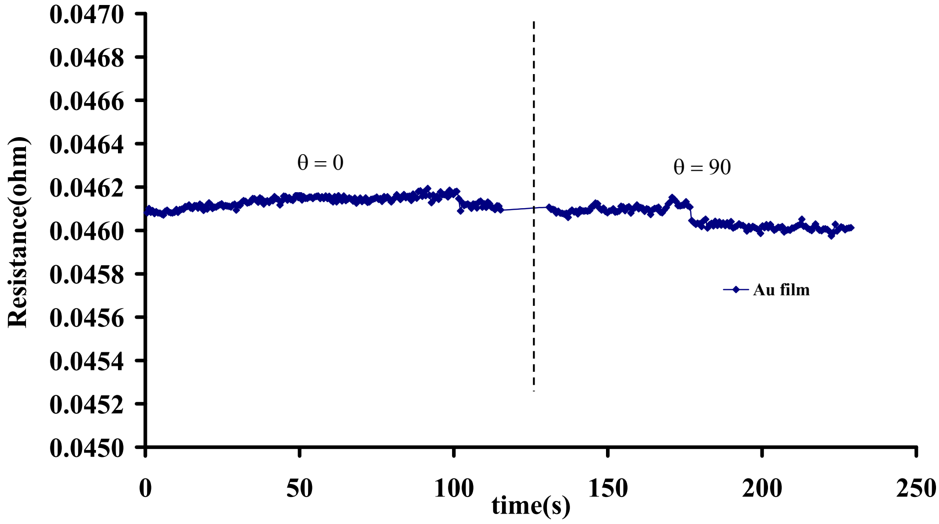

Figure 9. Change in resistance of gold film as the magnetic field is turned 90 degrees relative to the current.

CONCLUSIONS

The evaporated cobalt film exhibited AMR identified by the angle-dependent resistance in the magnetic field. The linear fit between resistance R_θ and $\cos^2\theta$ indicated an agreement between the experimental results and the equation proposed by McGuire and Potter. As a comparison, magnetoresistance measurements performed on non-ferromagnetic gold film showed angle-independent characteristics. Low-cost angle sensors could be developed based on cobalt films because, even at room temperature, their MR was very sensitive to the relative direction of current to the field.

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บทคัดย่อ

ยุทธนันต์ ปานสงฆ์ และ ชิตณรงค์ ศิริสถิตย์กุล

แอนไอโซโทรปิกแมกนีโตรีซิสแตนซ์ของฟิล์มโคบอลท์ที่เตรียมด้วยวิธีระเหย

ฟิล์มโคบอลท์บนแผ่นซิลิกอนเตรียมขึ้นด้วยวิธีระเหย โดยใช้โคบอลท์มวล 0.05 กรัม ระเหยเป็นเวลา 80 ถึง 240 วินาที จะได้ความหนาของฟิล์มตั้งแต่ 21.1 ถึง 67.7 นาโนเมตร คิดเป็นอัตราการเคลือบ 0.26 ถึง 0.32 นาโนเมตรต่อวินาที ฟิล์มโคบอลท์แสดงปรากฏการณ์แมกนีโตรีซิสแตนซ์ (MR) อยู่ในช่วง -0.0793% (เมื่อสนามแม่เหล็กตั้งฉากกับกระแสไฟฟ้า) ถึง +0.0134% (เมื่อสนามแม่เหล็กขนานกับกระแสไฟฟ้า) และอิ่มตัวในสนามแม่เหล็ก 220 มิลลิเทสลา MR ที่เกิดขึ้นเป็นแบบแอนไอโซโทรปิกแมกนีโตรีซิสแตนซ์ (AMR) เนื่องจากการเปลี่ยนมุมระหว่างสนามแม่เหล็กกับกระแส ไฟฟ้า (θ) ทำให้ความต้านทานไฟฟ้า (R_θ) เปลี่ยน ผลจากการทดลองสอดคล้องกับทฤษฎีเมื่อกราฟความสัมพันธ์ระหว่าง R_θ กับ $\cos^2\theta$ เป็นเส้นตรง จากการทดสอบกับสารที่ไม่ใช่แม่เหล็ก ได้แก่ทอง พบว่าฟิล์มทองไม่แสดง AMR โดยความต้านทานไม่ขึ้นอยู่กับมุมระหว่างกระแสไฟฟ้ากับสนามแม่เหล็ก

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