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Influence of Layer Thickness on Magnetoresistance Properties of Multilayered Thin Films

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Abstract: In this study, the magnetoresistance properties of multilayered structures consisting of five different combinations of Pt and Co thin layers were studied in the room temperature range. Thin films were prepared by using magnetron sputtering techniques in ultra-high vacuum conditions. It has been found that the percentage of MR decreases as the thickness of the spacer layer thickness increases. For 3 nm thickness, 0.16% MR ratio is obtained, while for 4 and 5 nm these values are 0.15% and 0.10% respectively. In addition, as reference layer thickness increases, MR values are 0.10%, 0.11% and 0.15%, respectively. These results show that the prepared thin film sets can be used in technological applications such as MR based sensors and spin field transistors.

Katman Kalınlığının Çok Katmanlı İnce Filmlerin Manyetodirenç Özelliklerine Etkisi

Anahtar Kelimeler
Katman Kalınlığı Etkisi,
Manyetodirenç,
Çok Katmanlı İnce Filmler

Öz: Bu çalışmada, beş farklı Pt ve Co ince tabaka kombinasyonundan oluşan çok tabakalı yapıların manyetodirenç özellikleri oda sıcaklığı aralığında incelenmiştir. İnce filmler, ultra yüksek vakum koşullarında magnetron püskürtme teknikleri kullanılarak hazırlandı. Ara tabaka kalınlığı arttıkça MR yüzdesinin azaldığı tespit edilmiştir. 3 nm kalınlık için %0.16 MR oranı elde edilirken, 4 ve 5 nm için bu değerler sırasıyla %0.15 ve %0.10'dur. Ayrıca referans katman kalınlığı arttıkça MR değerleri sırasıyla %0.10, %0.11 ve %0.15'tir. Bu sonuçlar, hazırlanan ince film setlerinin MR tabanlı sensörler ve spin alan transistörleri gibi teknolojik uygulamalarda kullanılabileceğini göstermektedir.

1. INTRODUCTION

Magnetic thin film structures, which consist of ferromagnetic layers separated by nonmagnetic metallic spacer, are widely used in magnetic recording media, spin field-effect transistors and magnetic sensors [1]. One of the main factors affecting the sensitivity of magnetoresistance (MR) based sensors is the interlayer coupling and its novel applications combining interfacial Dzyaloshinskii-Moriya interaction [2,3]. It is known that interlayer coupling strongly depends on quality of ferromagnet/spacer interfaces and electronic transport through the spacer.

The giant magnetoresistance (GMR) phenomenon is observed in magnetic multilayer structures where the magnetic layers of Iron (Fe), Cobalt (Co) and other magnetic metals are separated by non-magnetic layers (Chromium, Platinum, Iridium) several nanometers thick [4-8]. The thicknesses of these non-magnetic layers are chosen so that the exchange interaction between the spins of the ferromagnetic layers has an effective antiferromagnetic character. Thanks to this interaction, the magnetizations of adjacent ferromagnetic layers are oriented in opposite directions to each other (antiferromagnetic configuration). When this structure is placed in an external magnetic field, the magnetizations of the layers begin to align in parallel (ferromagnetic configuration), resulting in a significant change in electrical resistance. With nano-sized multilayer structures, the magnetoresistance reaching values above 100% at low temperatures in total determines the suitability conditions to produce next-generation magnetic sensors, read heads, magneto-resistive random-access memories, and other spintronic devices [9–11].

Ultrathin magnetic films and multilayer structures show the dimensional dependence of magnetic properties on film thickness, which is a transition from the two-dimensional behavior of films of 4-6 single-layer thickness to certain bulk values of films with tens of single-layer thickness [12–14]. Moreover, the properties of ultrathin magnetic films and nanostructures show high sensitivity to the effects of anisotropy created by the crystal field of a substrate or non-magnetic layers, and to the single-ion anisotropy and dipole-dipole interaction of the magnetic moments of atoms in the films [15–17]. The dimensional and anisotropy properties of these nano systems can be detected in their critical behavior because the properties of critical behavior of magnetic systems such as critical temperature and critical exponents are most sensitive to dimensional changes and the effect of magnetic anisotropy [14,18].

Here, we investigated the magnetoresistance properties of $[Pt/Co]_6$(2.4 nm)/Pt (x nm)/Co (y nm) ($3 \leq x \leq 5$, $2 \leq y \leq 4$ nm) sample sets changing the spacer and Co layer thicknesses.

2. MATERIAL AND METHOD

2.1. Experimental Procedure

The Silicon (Si) substrates were cleaned with an ultrasonic cleaner in acetone for 15 min and then in ethanol for 15 min, followed by washing with deionized water. Five different stacks with the following structures were fabricated (the numbers in parentheses denote the layer thickness in nm). Our sample set can be summarized as follows:

Sample 1: $[Pt/Co]_6$(2.4 nm)/Pt (3 nm)/Co(2 nm)
Sample 2: $[Pt/Co]_6$(2.4 nm)/Pt (4 nm)/Co(2 nm)
Sample 3: $[Pt/Co]_6$(2.4 nm)/Pt (5 nm)/Co(2 nm)
Sample 4: $[Pt/Co]_6$(2.4 nm)/Pt (5 nm)/Co(3 nm)
Sample 5: $[Pt/Co]_6$(2.4 nm)/Pt (5 nm)/Co(4 nm)

The substrates were annealed at 750 K for 90 min to clean the surface before deposition. All layers were deposited by using an ultrahigh vacuum magnetron sputtering unit on the Si (100) substrate with lateral dimensions of 10 mm × 10 mm. At the bottom of the multilayer system Pt buffer layer was grown with a thickness of 40 Å. Finally, the multilayer system was covered with 40 Å Pt cap layer against to the oxidation. The base pressure of the sputter chamber is $2x10^{-9}$ mbar and during the deposition Argon (Ar) pressure was $5x10^{-3}$ mbar. Pt layers were grown by DC generators while Co layers were grown by RF generators. The deposition rates for Pt and Co layers were 8.75 and 0.44 Å min^{-1}, respectively [19].

2.2. Magnetoresistance Measurements

Magnetoresistance measurements of multilayer magnetic thin films were made through four-point probe method at a constant applied current of 5 mA. Wire bonder was used for some of the contacts while silver cake was used for some. In magnetoresistance measurements, the film is placed in a sample container and the voltage values on the film are recorded in response to the current passing through the sample.
The schematic representation of the four-point measurement technique used in measuring the resistors of the prepared samples and the corresponding equivalent resistance circuits are given below in Figure 1. When the contact is received using four-point technique, the current is given from the external contacts and the voltage values are read from the internal contacts. In this way, only the resistance value from the example itself is read.

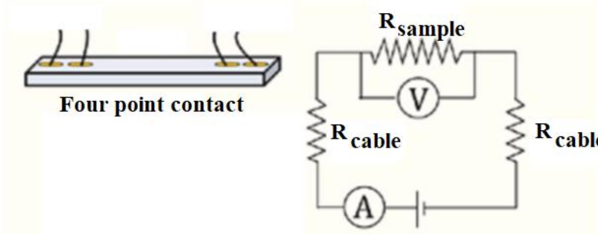

Figure 1. Schematic representation of four-point resistance measurement and circuit

In measurements such as anisotropic magnetoresistance (AMR) and giant magnetoresistance (GMR), contact points must be linear on magnetic films. For measurements such as anomalous Hall effect (AHE) and Planar Hall effect (PHE), contact points must be perpendicular to each other at the corners of the sample. To determine AMR and GMR behavior of the samples we prepared, four-point measurement techniques were applied, and measurements were performed in parallel and perpendicular geometries in the current and magnetic field plane.

The experimental system in which MR measurements are performed consists of electromagnets, computers, voltmeters that can read voltage at nanoscale, sample container and direct current power source. PCB (Printed Circuit Board) was used as a sample container. The two outer contacts on the circuit are prepared to apply current, while the two inner contacts are prepared to read voltage. The electromagnet, which is a magnetic field generator, is controlled by the computer while the voltage values are recorded from the nanovoltmeter.

3. RESULTS

The rate of resistance changes in samples (MR %) is calculated as follows,

$$MR(\%) = \frac{R(H) - R(\min)}{R(min)} x100 \tag{1}$$

Resistance on applied magnetic field is represented by R(H) and resistance on zero magnetic field is represented by R(min).

Figures 2-6 below are MR measurements obtained, respectively:

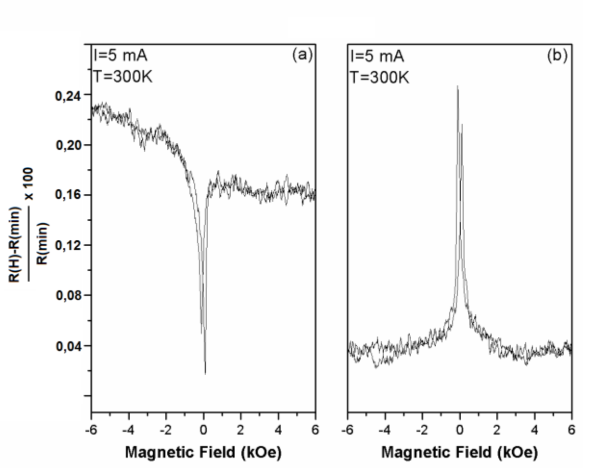

Figure 2. $[Pt/Co]_6$ (2,4 nm)/Pt(**3 nm**)/Co(2 nm) Magnetoresistance measurement in thin film a) Current and magnetic field parallel to each other b) Current and magnetic field perpendicular to each other

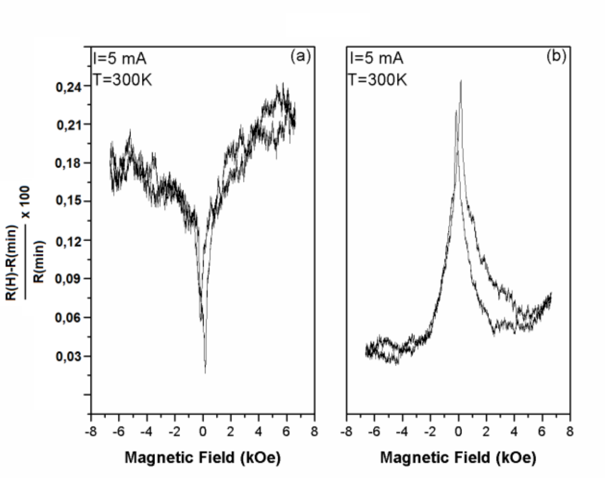

Figure 3. $[Pt/Co]_6$ (2,4 nm)/Pt(**4 nm**)/Co(2 nm) Magnetoresistance measurement in thin film a) Current and magnetic field parallel to each other b) Current and magnetic field perpendicular to each other

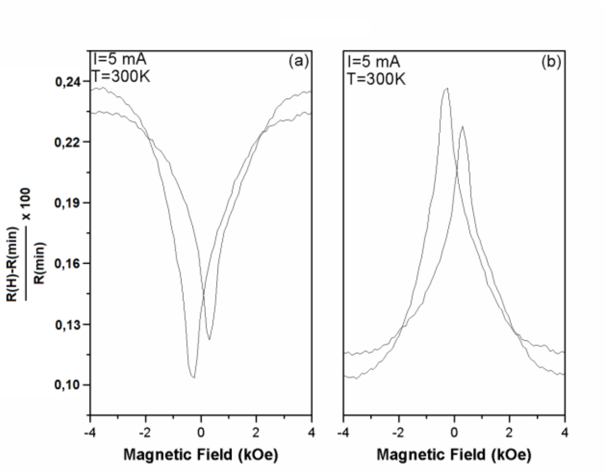

Figure 4. $[Pt/Co]_6$ (2,4 nm)/Pt(**5 nm**)/Co(**2 nm**) Magnetoresistance measurement in thin film a) Current and magnetic field parallel to each other b) Current and magnetic field perpendicular to each other

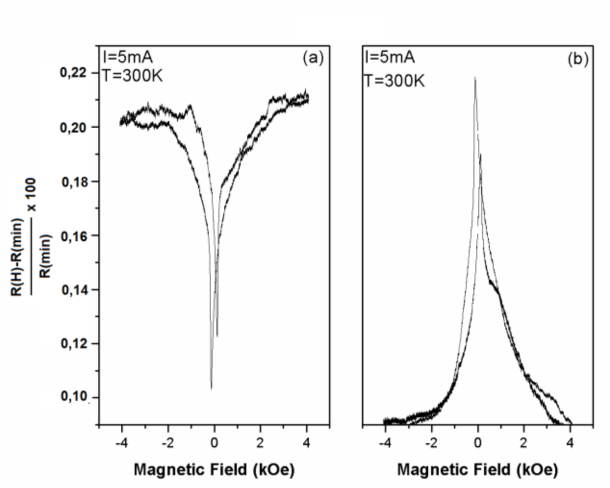

Figure 5. $[Pt/Co]_6$ (2,4 nm)/Pt(5 nm)/Co(**3 nm**) Magnetoresistance measurement in thin film a) Current and magnetic field parallel to each other b) Current and magnetic field perpendicular to each other

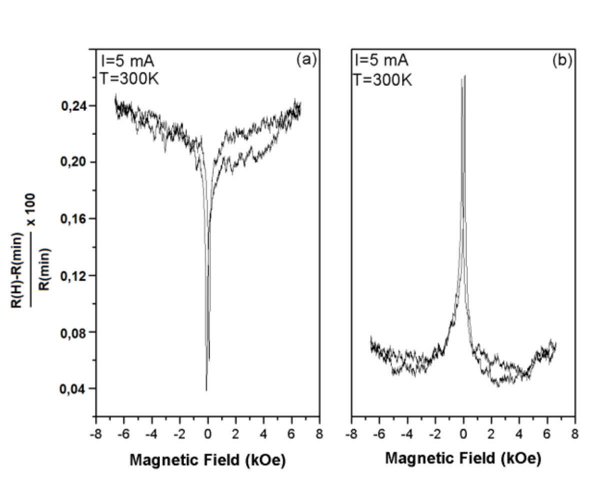

Figure 6. $[Pt/Co]_6$ (2,4 nm)/Pt(5 nm)/Co(**4 nm**) Magnetoresistance measurement in thin film a) Current and magnetic field parallel to each other b) Current and magnetic field perpendicular to each other

5 mA of current was applied to the samples during the measurements. And measured voltage values were recorded depending on the magnetic field. Resistance values were obtained by dividing the read voltage values into the applied current values. It is seen that the resistance values are not symmetrical on the vertical axis relative to the origin due to the geometry of the contacts prepared. Because all contacts cannot be placed in the film plane in order, besides the MR effect, anormal Hall effect and Planar Hall effect contributions can also be added to the measurement results. Since it is known that these contributions do not change coercive field values, there was no need to correct the shifts.

Coercive field values of 130 Oersted (Oe) for 3 nm Pt thickness, 312 Oe for 4 nm Pt thickness, 184 Oe for 5 nm Pt and 2 nm Co thickness, 135 Oe for 3 nm Co thickness, 110 Oe for 4 nm Co thickness were measured. These values clearly show that the thin films we prepared can be used in magnetic sensor applications.

In such multilayer systems, there are two advantages of having the thickness of ferromagnetic layers close to each other (low net moment). Low net moment limits the dipole areas arising from the interaction of the reference and free layer. Second, the low moment allows the reference layer to interact weakly with the external field.

As stated in Equation 1, the MR ratios obtained when applied for figures 2, 3, 4, 5 and 6 were obtained as 0.16, 0.15, 0.10, 0.11 and 0.15, respectively. It is seen in the above figures that the percentage of MR decreases as the thickness of the spacer layer thickness increases. The exponential variation of the MR amplitude is related to the flow of polarized conduction electrons across the interlayer from one ferromagnetic layer to the next. For 3 nm thickness, 0.16% MR ratio is obtained, while for 4 and 5 nm these values are 0.15% and 0.10%, respectively. In addition, as reference layer thickness increases, MR values are 0.10%, 0.11% and 0.15% respectively [20, 21]. It can be seen from figures 4, 5 and 6 that the MR amplitude increases significantly when the thickness of the Co layer we use as the reference layer increases.

4. DISCUSSION AND CONCLUSION

Spacer layer thickness (Pt) increased from 3 nm to 5 nm and the magnetoresistance decreases gradually. This indicates that magnetoresistance is due to the exchange of polarized electrons transferred from one ferromagnetic layer to another [22]. The exponential variation of the MR amplitude is related to the flow of polarized conduction electrons through the decency from one ferromagnetic layer to another. Scattering on the interface reduces current perpendicular to the surface and therefore also decays MR amplitude. When the thickness of the Co layer we use as the reference layer increases, it is seen that the MR amplitude increases conspicuously.

The magnetic field sensitivity provided by the GMR structure consists of two layers, the hard reference layer, and the soft layer, which are not sensitive to the external field. The relative angle of the magnetization vectors of the two layers controls the resistance of the device.

In general, spin transfer torque and the GMR effect are closely related. So, to obtain one, you must obtain the other. For a GMR magnetic sensor and reading header, one of the magnetic layers is less sensitive to the external magnetic field (the reference layer), while the other is sensitive to the external field (the free layer). For such a design, the current depends only on the relative angles of the magnetizations of the two layers through the GMR effect i.e. the change in resistance and affect magnetization through the formation and warming of Oersted fields.

As a result, with tuning the thickness of these types of thin films or nanostructures, it is seen that thin films we have prepared can be used in technological devices such as magnetic sensor applications and reading heads.

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