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ORIGINAL PAPER

Effect of Surface Oxidation on the Magnetization Reversal of Cobalt Planar Wires

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Abstract The influence of the antiferromagnetic layer of cobalt oxide on the magnetization reversal of a submicron cobalt planar wire was studied using the magneto-transport measurements. For pure Cobalt (Co) planar wires of width less than 1.2 μm, length of 30 μm, and thickness of 30 nm, the shape anisotropy dominates the magnetic behavior revealing all characteristics of a single domain structure. With oxidation, there is a thin layer of CoO on top of the Co layer and the exchange coupling between the CoO (antiferromagnet) and Co (ferromagnetic) layers may suppress the shape anisotropy induced single domain structure and the typical switching behavior of magnetization reversal. The magnetic configuration and magnetization reversal are determined by the competition of unidirectional anisotropy and exchange coupling constant.

Keywords Exchange coupling · Single domain structure · Shape anisotropy · Magnetization reversal

1 Introduction

The progressing technique in fabricating sub-micrometric magnetic systems produces increasingly new physical phenomena and poses challenges to established models of magnetic behavior. Understanding the fundamental magnetic properties in reduced scales can lead to important developments in pioneering spintronics devices [1]. Recently, patterned spin valve sub-micrometric structures have been extensively utilized in numerous magnetoelectronics applications [2]. Therefore, investigations of exchange coupling between antiferromagnetic (AFM) and ferromagnetic (FM) wires have become of considerable experimental and theoretic interest.

For submicron ferromagnetic wires of high shape anisotropy both coherent rotation and magnetization curling mechanisms are believed to be responsible for magnetization reversal. The switching field (H_{SW}) characterizing the abruptly irreversible change in the magnetization has usually been analyzed. The magnetic configuration is mainly dominated by the shape anisotropy [3–6]. It has been known that the interfacial exchange coupling of AFM/FM layers could give rise to an induced unidirectional anisotropy resulting in a shift of magnetic hysteresis loop along the field axis [2, 7–11]. The magnetization reversal asymmetry is of crucial important to elucidate unidirectional behavior. Nevertheless, the influence of exchange bias on the magnetization reversal of the high shape anisotropic magnetic wires is rarely explored and a comprehensive understanding requires further study.

Magnetoresistance (MR) measurements have been found to be a well qualified tool for studying the magnetization reversal processes because the anisotropic magnetoresistance (AMR) effect is sensitive to the magnetization distribution during the reversal process. Parallel alignment of magnetic moment with applied current results in the maximum resistance while a minimum resistance results from the perpendicular alignment. In this work, we have made a systematic magneto-transport investigation on a series of patterned Co (single layer) and CoO/Co (bi-layer) planar wires to rule out the effect of AFM/FM exchanging coupling on magnetization reversal of high shape anisotropic wires.

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2 Experimental Details

Our Co wires are prepared by standard e-beam lithography, DC sputtering, and lift-off techniques on SiN coated Si(100) substrates. The length and thickness of all samples are kept constant, $\ell = 30.1 \pm 1.5$ µm and $t = 30 \pm 2$ nm. Several widths w are chosen ranging from 0.2 µm to 10 µm, respectively. Some planar wires are in situ capped with a 3 nm thick Au layer to prevent from oxidation. Others are forced oxidized to form a layer of CoO by exposing in the air for certain amounts of time (either 5 or 30 mins) before depositing Au. Non-magnetic Au contacts are arranged for 4-terminal electrical transport measurement.

Magneto-transport is performed in a pumped ^{4}He cryostat and at the center of an electromagnet. Sample resistance is obtained using a low frequency resistance bridge with a low excitation current ($\leq$0.1 mA). Current is applied along the long axis of the sample. Temperature dependent resistance behavior of all samples follows the Mathiessen law above 50 K and is metallic-like down to 15 K. The resistance increases slightly with decreasing temperature below 10 K indicating that all samples are more or less disordered. The disorder of the forced oxidized sample is worse. For magnetoresistance presented here, the magnetic field is applied in the sample plane making an angle θ relative to the applied current. The complete hysteresis loop of in-plane MR is measured for different angles (θ, within an error of 1°) between the long axis (current) and applied magnetic field. As reported earlier, training effect is present in the CoO/Co system [2, 9]. All presented data were taken after field-sweeping couples of loops at 10 K.

3 Results and Discussion

The magnetic structure of a ferromagnetic micro-element depends on its geometrical factors such as the critical length and the aspect ratio, $m = \ell/w$. In a series of pure Co planar wire of length $\ell = 20$ µm and thickness $t = 30$ nm, we found that the shape-induced magnetic structure transition occurs at $m = 20$. For wire width less than 1 µm, a typical single domain state with all magnetic moments along the long axis was observed. A typical abrupt change in magnetic configuration and magneto-transport at the switching is its characteristic [6, 8]. For wider wires of $w > 1$ µm, the remanent state is a multi-domain configuration, the magnetization reversal is via the domain expansion. The transition is expected by the theoretical model which considers the lowest free energy state for prolate spheroids at remanence [3]. The results are also in consistence with others in magnetic force microscopy and magneto-transport measurements [6, 8].

Here we focus on the so called "single domain" wires. The transition for the $\ell = 30$ µm series is around $m = 25$ and, correspondingly, $w = 1.2$ µm. Figure 1 is the longitudinal magnetoresistance of three Co wires of $w \sim 0.6$ µm but different degrees of oxidation. $\Delta R/R_{\parallel}$ is defined as $(R(H) - R_{\max})/R_{\parallel}$ where $R_{\parallel}$ is the resistance at saturation when the applied current is along the magnetic field. In general, $R_{\parallel}$ is the maximum, $R_{\max}$, under the consideration of anisotropic magnetoresistance effect. As seen in Fig. 1, the top black curve shows the typical switching behavior symbolizing the single domain reversal mechanism. However, a slight magnetic field shift appears indicating an AFM/FM coupling induced exchange bias. H_{ex} is around 120 Oe by calculating $|H_{\mathrm{sw1}} + H_{\mathrm{sw2}}|/2$. In addition, resistance does not jump back to $R_{\parallel}$ right at the switching field and instead, a smooth approach after the jump (85 %). The behavior is somehow different from the "single domain" wires of pure Co series. For other two forced oxidized wires, in contract, the curve is analog to that of the "multi-domain" wire. The resistance jump disappears. The resistance decreases smoothly when magnetic field is reduced from the saturation field implying that the magnetic moments do not favor to align along the wire axis. The resistance drop ratio at coercive field can be more than 40 % of AMR magnitude. Besides, the asymmetry of magnetoresistance curve and the magnetic field shift of the hysteresis loop are clearly visualized. H_{ex} is 210 Oe for the one with oxidation time in 30 mins. The exchange bias increases with increasing the degree of oxidation. Due to the favor of anti-parallel alignment of magnetic moments of both AFM and FM layers at interface, the magnetic moments of FM layer at interface are not completely align the long axis when magnetic field is applied along the magnetic moment of AFM interfacial layer. This leads to a resistance decrease at −2.5 kOe comparing with +2.5 kOe. We conclude that the strong coupling of AFM/FM layers is detrimental to shape anisotropy in-

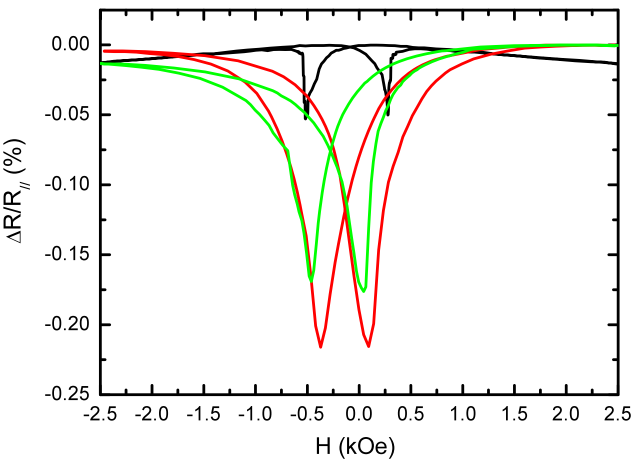

Fig. 1 Longitudinal magnetoresistance of three Co wires (width ∼0.6 µm) with different degrees of oxidation, barely oxidized (*black*), medium oxidized (*red*), and strong oxidized (*green*), at $T = 10$ K (Color figure online)

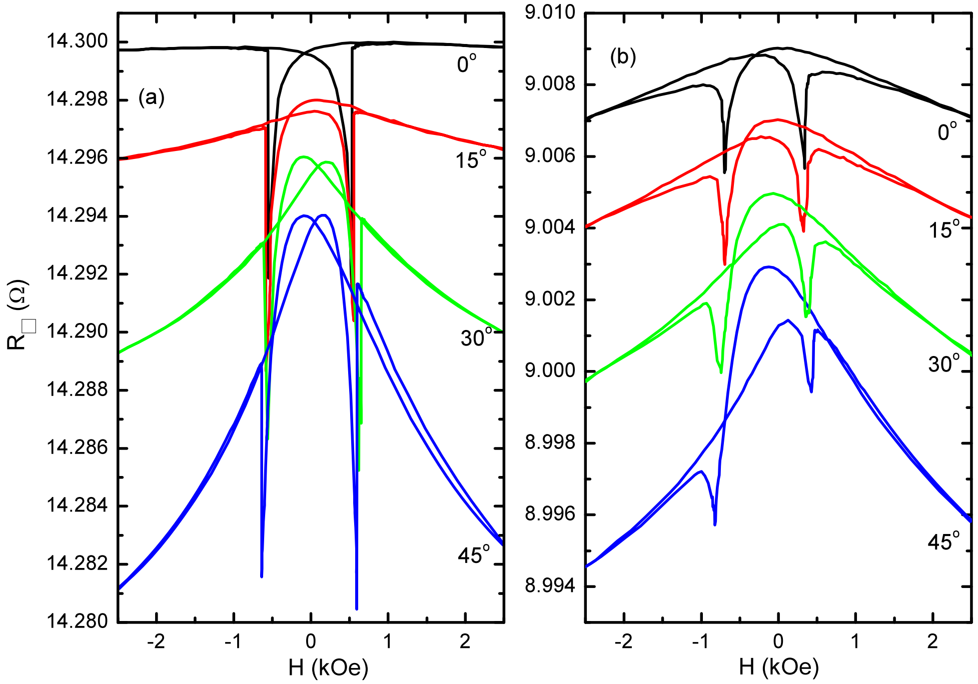

Fig. 2 The angular-dependent magnetoresistances of two barely oxidized Co wires of $w \sim 0.4$ μm (**a**) and $w \sim 0.9$ μm (**b**) at $T = 10$ K, respectively. The angle θ of the in-plane magnetic field relative to the long axis of the wire axis is indicated on the side of each line. The *curves* are vertically shifted by multiples of 0.002 for clarity (Color figure online)

duced single domain structure and also to the corresponding magnetization reversal behavior in two forced oxidized wires. AFM domains pinned the moments of the adjacent FM layer, multi-domain structure forms and magnetic reversal is via domain expansion.

The forced oxidized narrow wires behave just like wider wires of small aspect ratio ($m < 25$, $w > 1.2$ μm). We put our attention on barely oxidized wires. The angular-dependent magnetoresistances of two Co wires of $w \sim 0.4$ μm and $w \sim 0.9$ μm are plotted in Fig. 2, respectively. Notice that the curves of $\theta \neq 0$ are vertically shifted for clarity. An irreversibly V-shaped discontinuity in low field can be clearly found for all angles. The jump of magnetoresistance indicating the transition from curling to coherent rotation occurs at the switching field H_{sw}. H_{sw} slightly increases with increasing θ at low angle as expected by the Aharoni model for a prolate ellipsoid [1, 3]. Both wires demonstrate the "single domain" characteristics in accordance with theoretical prediction and experimental data of pure Co planar wires. Both wire widths are less than 1.2 μm which is critical width for the domain structure transition at remanence for the $\ell = 30$ μm series.

Nevertheless, there is little discrepancy of these curves with that of truly single domain wires. Taking a care check, the asymmetric shape and magnetic field shift of the curve are found although the scenarios are not as vivid as that of two forced oxidized wires in Fig. 1. Hence, there is certainly a thin antiferromagnetic CoO layer around the Co layer. It seems that Co layer is unavoidable to oxidize even with the sequent deposition of Au layer atop. Both wires, $w = 0.4$ μm (a) and $w = 0.9$ μm (b) are under the same fabrication process. Combined with data of various widths, the magnetoresistance curves seems smoothly but monotonically deviate from perfectly single domain behavior with increasing wire width. It is known that the shape-induced anisotropic energy K_u decreases with increasing wire width following the $1/w$ relationship [7]. AFM/FM exchange coupling may have less effect on magnetization reversal of single domain wires with high K_u. The magnetization reversal is determined by the competition between exchange coupling J and K_u.

4 Summary

In summary, AFM/FM coupling may suppress the magnetization curling mechanism of high aspect ratio magnetic wire which has strong shape-induced unidirectional anisotropy. For strong AFM/FM coupling, multi-domain forms at remanent and magnetization reversal occurs by domain expansion. For less AFM/FM coupling, the magnetization curling and single domain structure are less affected for high anisotropic wires. The deviation is progressively increased with increasing wire width (reducing the aspect ratio).

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