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Giant magnetoresistance and structural properties in Co/Cu/Co sandwiches with Si and Cr buffer layers

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Abstract

Cobalt 5.5 nm/Cu 3 nm/Co 5.5 nm sandwiches with Si and Cr buffer layers were prepared by ultra-high vacuum electron beam evaporation. A large in-plane anisotropy of the giant magnetoresistance (GMR) effect was found in Si buffered sandwiches when the buffer layer thickness was equal to or larger than 0.9 nm. In the easy axis, the GMR effect reached a value of 5.5% with a high field sensitivity of approximately 0.7%/Oe, while in Cr-buffered Co/Cu/Co sandwiches, the GMR effect showed only in-plane isotropic properties with a maximum GMR value of 6%. The XRD spectrum and HRTEM image revealed that there exists a Co_2Si compound between the Si buffer and the lower Co magnetic layer. All these results indicate that the anisotropic GMR effect in Si-buffered sandwiches results from the cobalt silicide between the Si buffer and the lower Co magnetic layer.

Keywords: Giant magnetoresistance; Co/Cu/Co sandwich; Buffer layer; Anisotropy

1. Introduction

Since the discovery of the giant magnetoresistance (GMR) effect in Fe/Cr multilayers [1], considerable attention has been paid in the literature to this effect observed later in many other multilayers such as Co/Cu [2], Co/Ru [3], and NiFe/Cu [4]. At present, the Co/Cu multilayers seem to be of the greatest interest because of the large GMR effect and of its weak temperature dependence [2,5]. Because of these properties, this system could be a candidate for applications.

It was reported that the buffer layer played an important role in the enhancement of the MR ratio in magnetic multilayers. Large MR ratios were obtained in Co/Cu multilayers with a Fe buffer layer [2] and in NiFe/Cu/Co/Cu multilayers with a Cr buffer layer [6]. Commonly, it was considered that the buffer layer could improve the flatness of the multilayers, so that the MR ratio was enhanced. Confusingly, there was also a report of large MR ratio in multilayers without any buffer layer [7]. Considering that a sandwich consisting of two magnetic and one non-magnetic layer is the basic unit of multilayers, the effect and the importance of a buffer layer on its GMR effect should be easily found. In this work, semiconductor material Si and transition metal Cr were used as buffer layers for Co/Cu/Co sandwiches. It was found that a strong in-plane anisotropic GMR effect related to cobalt silicide appeared in Si-buffered sandwiches, while only an isotropic GMR effect with larger saturation field in Cr-buffered ones was found.

2. Experiment

The sandwiches were prepared using a Balzers ultra-high vacuum (UHV) electron beam evaporation

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system. The base pressure was approximately 5×10^{-7} Pa and the working pressure was approximately 5×10^{-6} Pa. The deposition rates were 0.05 nm/s. Conventionally cleaned Si(100) wafers with a size of 5×15 mm^2 were used as substrates. Cobalt 5.5 nm/Cu 3 nm/Co 5.5 nm sandwiches were deposited after the deposition of a Si or Cr buffer layer. The thickness of each buffer layer, ranging from 1 nm to 14 nm, was controlled by a quartz oscillating thickness monitor and was calibrated by high-resolution transmission electron microscopy (HRTEM). The hysteresis loop of the samples was measured by a vibrating sample magnetometer (VSM). The film texture was investigated using an X'pert Philips X-ray diffractometer (XRD) with a Cu K_α target and the microstructure of the sandwiches was observed by HRTEM. All the characterizations were performed at room temperature. The MR is defined as $MR = (R - R_S)/R_S$ where R_S is the resistance at saturation field. The applied field H along the sample plane was parallel to the measurement current.

3. Results and discussion

For sandwiches with a Si buffer layer, the MR value increases quickly from 0.3% to 4.8% when the Si buffer layer thickness increases from zero to 0.6 nm. A strong anisotropic GMR effect appeared when the Si thickness was equal to or larger than 0.9 nm. Fig. 1 shows the typical results obtained in a Si 1.5 nm/Co 5.5 nm/Cu 3 nm/Co 5.5 nm sandwich. α is the angle between the applied field H and the length side. When the field is applied along the length side ($\alpha = 0°$), the maximum MR value is 5.5% with a sensitivity of 0.7%/Oe. The MR value decreases to 4.2% when the field becomes perpendicular to the length side ($\alpha = 90°$). At the same time, the saturation field also increases from approximately 90 Oe to approximately 150 Oe, resulting in a very small sensitivity of 0.06%/Oe. For a Si thickness less than 0.9 nm, the MR value is the same in any direction, also with low field sensitivity. Correspondingly, the sandwiches presented similar

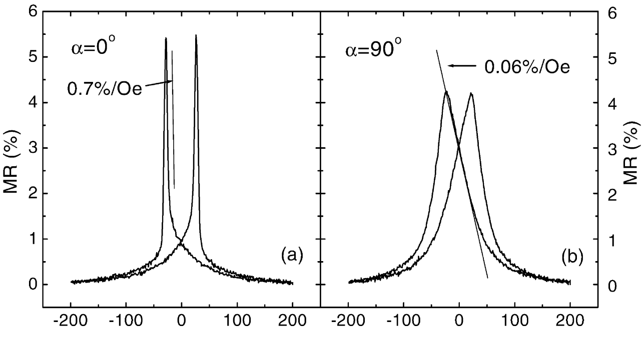

Fig. 1. The magnetoresistance curves for Si(100)/Si 1.5 nm/Co 5.5 nm/Cu 3 nm/Co 5.5 nm with (a) $\alpha = 0°$ and (b) $\alpha = 90°$.

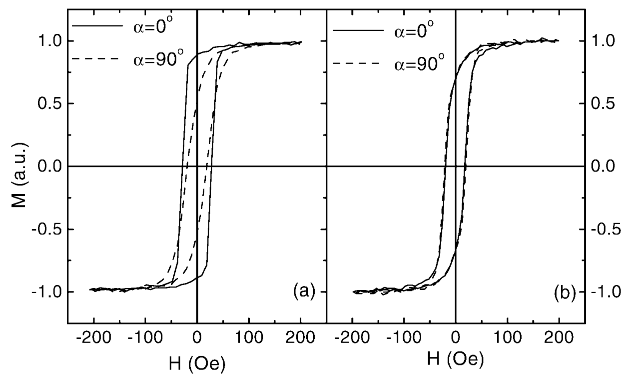

Fig. 2. Normalized hysteresis loops for Si(100)/Si t_{Si}/Co 5.5 nm/Cu 3 nm/Co 5.5 nm with $t_{Si} = 1.5$ nm (a) and 0.6 nm (b). α is the angle between field H and easy axis.

anisotropic in-plane magnetization for thick Si buffer layers. Shown in Fig. 2a are hysteresis loops measured in the same sample in Fig. 1. One notes that in the easy axis direction ($\alpha = 0°$), the curve has a clear rectangular shape with a coercivity of 28 Oe, meaning that the magnetic moments could turn over quickly as the applied field changes, so that we get larger sensitivity in this direction. In the hard axis direction ($\alpha = 90°$), however, the magnetic moments move slowly with the applied field, resulting in a smaller sensitivity. The same process takes place in those sandwiches with thinner Si buffer layers since they have similar magnetization curves (Fig. 2b) to that in Fig. 2a measured at $\alpha = 90°$.

In Cr-buffered sandwiches, the GMR effect was found to be isotropic for all Cr buffer layer thicknesses. With increasing Cr thickness to 8 nm, the GMR value increased gradually to its maximum value of 6%. After that, the MR value decreased for much thicker Cr buffer layers due to current shunting. Fig. 3 shows the typical field dependence of MR and magnetization for a Cr 8 nm/Co 5.5 nm/Cu 3 nm/Co 5.5 nm sandwich. It can be noticed that the saturation field is much increased to approximately 200 Oe. From the hysteresis loop in Fig. 3b, a coercivity of 86 Oe was obtained. In order to understand the origin of the large difference in coercivity of a Co/Cu/Co sandwich using either Si or Cr buffer layers, we prepared two Si 3 nm/Co 5.5 nm and Cr 8 nm/Co 5.5 nm bilayer samples. It was found that the coercivities of the Si/Co bilayer were only approximately 30 Oe with in-plane magnetic anisotropy, while for the Cr/Co bilayer, its coercivity increased to a value of approximately 200 Oe. The same coercivity enhancement was observed when Co-based alloy was grown on Cr buffer layer [8] and was attributed to the bcc Cr structure promoting the formation of a hcp Co-based thin film, resulting in the hcp c-axes being distributed in the plane of the film. It is clear now that the magnetic anisotropy in Si-buffered sandwiches comes from the lower Co magnetic layer

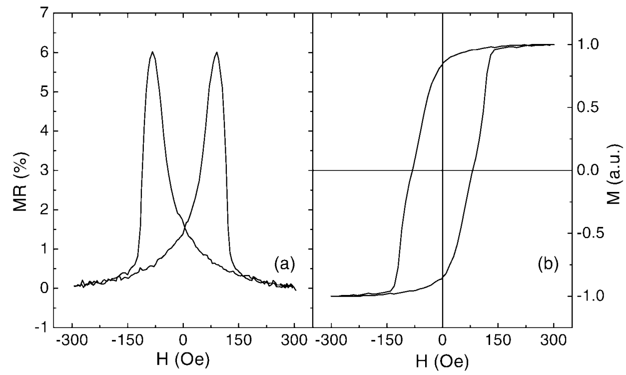

Fig. 3. The magnetoresistance curve and normalized hysteresis loop for Si(100)/Cr 8 nm/Co 5.5 nm/Cu 3 nm/Co 5.5 nm.

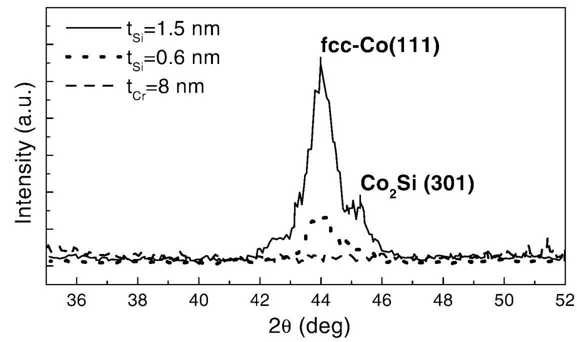

Fig. 4. The high-angle XRD patterns for sandwiches Si(100)/Si t_{Si}/Co 5.5 nm/Cu 3 nm/Co 5.5 nm with $t_{Si} = 0$, 0.6 and 1.5 nm and sandwich Si(100)/Cr 8 nm/Co 5.5 nm/Cu 3 nm/Co 5.5 nm.

and that the Cr buffer layer enlarged the coercivity of its neighboring Co layer, resulting in the larger coercivity of the sandwich.

Since we did not apply any magnetic field to the sample during the deposition process and used the same procedure for the fabrication of all sandwiches, the mechanism of the in-plane magnetic anisotropy appearing only in the lower Co layer of Si buffered sandwiches remains to be studied further. It may result from its special structure. To confirm this hypothesis, an XRD measurement was performed on Si- and Cr-buffered sandwiches. As shown in Fig. 4, there is a strong peak at approximately $2\theta = 44°$ in all Si-buffered samples, which was assigned to fcc-Co(111) together with some contribution from fcc-Cu(111). Moreover, there is also a shoulder peak at approximately $2\theta = 45.3°$ for a Si buffer layer equal to or thicker than 0.9 nm. This peak has been attributed to Co_2Si(301). According to the theoretical analysis, the average atom distance in the Co_2Si(301) plane is 0.258 nm, which is close to that in fcc-Co(111), 0.251 nm. Also the atom arrangement of these two kinds of planes are all regular hexagon. It is easy for fcc-Co(111) to grow on Co_2Si(301). On the other hand, there is only a good repeatability of atom arrangement in the [010] direction in the Co_2Si(301) plane. The repeatability of atom arrangement is dependent on the preferred-direction, which will influence the atom arrangement in the fcc-Co(111) grown on Co_2Si(301) plane, leading to the observed in-plane magnetic anisotropy. The structural properties of the sandwiches were further investigated by cross-sectional HRTEM. There were only randomly oriented polycrystalline grains in Cr-buffered sandwiches. The Cr buffer seemed to grow in pillar-shaped grains on a Si substrate. For an evaporated Si buffer layer, it is an amorphous state as shown in Fig. 5. From the HRTEM image, it is evident there is a Co_2Si layer, approximately 2 nm thick, between the Si buffer layer and the lower Co magnetic layer. The thickness of the α-Si buffer layer is less than the set value due to the consumption of Si to form Co_2Si. This observation is in agreement with the above XRD result and supports our hypothesis.

4. Conclusions

A large anisotropy of GMR effect was found in Si-buffered Co/Cu/Co sandwiches when the thickness of Si buffer layer was equal to or larger than 0.9 nm. With H parallel to the easy axis, the GMR effect reached a value of 5.5% with a high field sensitivity of approximately 0.7%/Oe for a Si buffer thickness of 1.5 nm, which differs from the GMR value of 4.2% and the sensitivity of 0.06%/Oe with H perpendicular to the easy axis. While in Cr-buffered Co/Cu/Co sandwiches, the GMR effect showed only in-plane isotropic

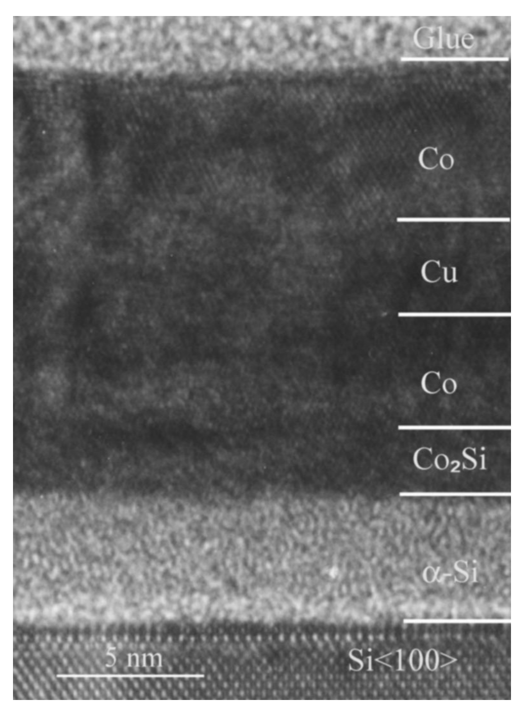

Fig. 5. Cross-sectional HRTEM image of sandwich Si(100)/Si 5 nm/Co 5.5 nm/Cu 3 nm/Co 5.5 nm.

properties. Its MR ratio increased to a maximum of 6% gradually with Cr thickness up to 8 nm, and then decreased due to the shunting effect in Cr buffer layer, which is in contrast to that quick increase of MR ratio with Si thickness and then a stable MR ratio in Si-buffered Co/Cu/Co sandwiches. XRD results and HRTEM observation revealed that there exists a Co_2Si compound between the Si buffer and the lower Co magnetic layer. All the results above demonstrate that the observed Co_2Si compound is responsible for the anisotropic GMR effect appearing in Si-buffered Co/Cu/Co sandwiches.

Acknowledgements

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