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Direct experimental study of the microscopic remagnetization mechanism in Co/Cu magnetic superlattices

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Abstract

Using the magneto-optical indicator film technique, the correlation between the magnitude of the giant magnetoresistance (GMR) and the micromechanism of the magnetization reversal of electrodeposited Co/Cu superlattices are investigated for a range of Cu spacer thicknesses. The multilayers showing vanishing GMR exhibit a cooperative spin behaviour, which is similar to that exhibited by thin ferromagnetic films with in-plane fourfold anisotropy. In contrast, superlattices with a substantial GMR demonstrate partially coupled noncollinear spin configurations, which are probably responsible for the observed giant magnetoresistance phenomenon.

Keywords: Metallic multilayers; Giant magnetoresistance; Magnetization reversal; Domian structure

The correlation between magnetic and transport properties of thin-film metallic multilayers has been the subject of many studies during the past decade. Most of this activity has focused on the oscillatory exchange coupling between ferromagnetic (FM) layers separated by a nonmagnetic spacer layer and on the giant magnetoresistance (GMR) associated with such layered structures. In particular, the Co/Cu superlattices are of potential interest as elements in magnetic sensors because of the substantial GMR value, up to $\sim$65% measured for sputtered films at room temperature [1,2]. The increase in resistance occurs with decreasing external magnetic field as the interlayer bilinear exchange coupling produces antiferromagnetic (AF) spin alignment of neighboring Co layers. The situation seems to be even more intriguing due to a biquadratic interaction, which favors orthogonal spin alignment in adjacent FM layers leading to noncollinear spin configurations. This coupling originates most likely from the multilayer defects such as interface roughness and pinholes [3–5]. Since in the simplest GMR model, the magnetoresistance depends on the angle between magnetic moments in successive layers, the study of the occurrence of noncollinear spin structures in magnetic multilayers may give some clues to increasing the GMR effect.

In this paper, we present a study of the micromechanisms of the magnetization reversal of electrodeposited Co/Cu multilayers in relation to the GMR magnitude. $[\mathrm{Co}(16\ \text{Å})/\mathrm{Cu}(d_{\mathrm{Cu}})]_{200}$ multilayers used in our study were electrochemically deposited onto Si(0 0 1) substrates which had a 200 Å copper seed layer [6]. The thickness of the Cu layers, d_{Cu}, was varied in a range from 5 to 40 Å.

The magnetoresistance was measured using a conventional four-point probe technique. Magnetic hysteresis loops were obtained by vibrating sample magnetometry. The magneto-optical indicator film (MOIF) technique was used to image magnetic domain structures during

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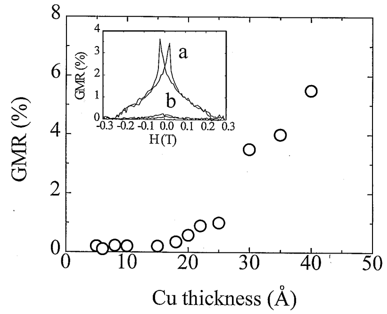

Fig. 1. Dependence of the magnetoresistance ratio on the thickness of Cu spacer for Co/Cu multilayers electrodeposited on Si(1 0 0) substrates. $\Delta R/R = (R_{max} - R_{sat})/R_{sat}$. Inset: Magnetoresistance curves for the Co/Cu multilayer with $d_{Cu} = 30$ Å (a) and $d_{Cu} = 8$ Å (b).

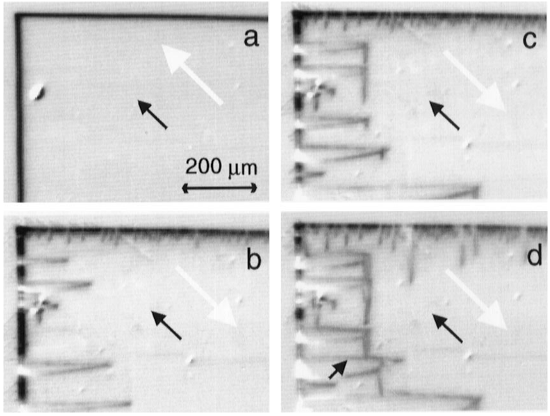

Fig. 2. MOIF images of the [1 1 0] easy-axis magnetization reversal in Co/Cu multilayer with $d_{Cu} = 8$ Å. $\mu_o H = 17.1$ mT (a), −1.68 (b), −1.96 (c), and − 2.37 (d). White arrows indicate the direction of the applied filed, black arrows show the magnetization in domains.

the remagnetization of the multilayers. The stray field around domain walls, edges and defects of the multilayer were imaged due to variations in the Faraday effect in an overlying indicator film with in-plane anisotropy [7]. All measurements were performed at room temperature.

The 'longitudinal' magnetoresistance $\Delta R/R$ of multilayers as a function of the Cu layer thickness is shown in Fig. 1. In contrast to sputter deposited Co/Cu superlattices, we observed no peaks in the GMR at Cu thicknesses corresponding to expected maxima for interlayer AF coupling. The dependence of $\Delta R/R$ upon d_{Cu} was a steadily increasing function up to $d_{Cu} \approx 40$ Å. The inset in Fig. 1 shows a typical GMR curve for the specimen with $d_{Cu} = 30$ Å.

All our specimens were found to exhibit in-plane fourfold magnetic anisotropy with easy axes along [1 1 0] and [$\bar{1}$ 1 0] directions [6]. However, multilayers with thin and thick Cu spacers demonstrated different hysteresis properties. For example, the hysteresis loop of the sample with the Cu layer thickness $d_{Cu} = 8$ Å is perfect square with a coercive force of about 2.7 mT. The sample having the thicker Cu spacer, $d_{Cu} = 30$ Å, possesses a slightly diminished remanet magnetization and its coercive force is about 20 mT. Note the GMR scales inversely with the reduction of the remanent magnetization. This same relationship was also found earlier for sputter deposited multilayers [8].

Fig. 2 shows the MOIF easy-axis reversal patterns of the $[Co(16 Å)/Cu(8 Å)]_{200}$ multilayer. This sample demonstrated almost no GMR. Sample edges are parallel to the [1 0 0] and [0 1 0] directions, while the easy axes lie along $\langle 1\,1\,0 \rangle$. First, the specimen was magnetized to saturation along the easy axis and then the applied field was reversed (Fig. 2b–d). The spike-like domains nucleated at film edges due to edge magnetostatic fields and quickly propagated over the specimen. Curiously, secondary domains with the perpendicular tooth orientation occurred at spike heads, due probably to the stray field concentration. The domain wall motion was followed by the spin rotation.

In contrast, specimens, which showed measurable GMR, exhibited completely different domain reversal behaviour. Fig. 3 shows MOIF patterns of the $[Co(16 Å)/Cu(30 Å)]_{200}$ sample during magnetization along the easy axes of magnetization. The set of patterns in Fig. 3 is associated with a minor hysteresis loop. In general, similar to the above case, the easy-axis reversal proceeds by the nucleation and motion of domain walls. However, it starts by the nucleation of a zigzag domain wall (further referred to as DW-I) at the [1 0 0] specimen edge (Fig. 3a). The teeth of the wall are directed along the [0 1 0] axis. With increasing field, a new domain wall with teeth parallel to the [1 0 0] axis (we denote this wall as DW-II) nucleates at the [0 1 0] edge and translates into the sample interior (Fig. 3b).

Fig. 3c–f illustrate a surprising phenomenon of the 'interpenetration' of those domain walls. Fig. 3c shows the domain configuration after stopping the magnetic field sweep at the $\mu_0 H = -18$ mT and applying the field of 11.3 mT in the opposite direction. This results in the nucleation and propagation of a new domain wall (bright contrast) which seems to be similar to the DW-I. This new domain wall passes through the DW-II (Fig. 3d) to annihilate with the DW-I (Fig. 3f). The DW-II annihilates with its counterpart as shown in Fig. 3e.

This unexpected domain-wall behaviour can be understood in terms of DW-I and of DW-II being associated with different layers of the compositional superlattice. There are several possibilities for the origin of a wall through the multilayer thickness. First, both DWs-I and II could consist of many domain walls localized in

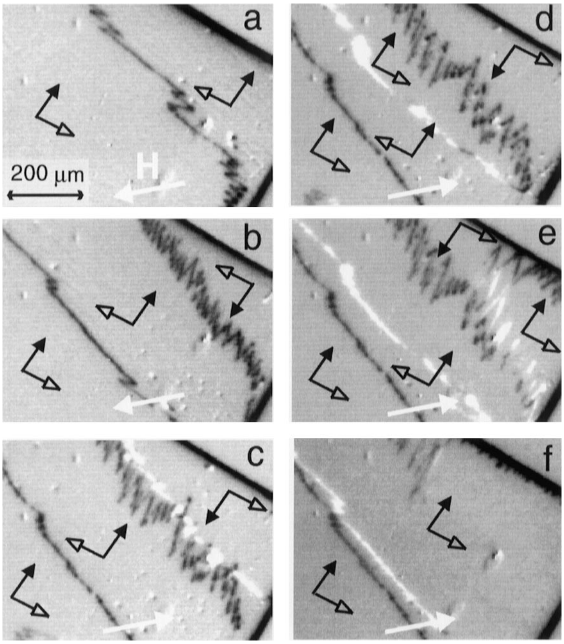

Fig. 3. MOIF images of the [1 1 0] easy-axis magnetization reversal in Co/Cu multilayer with $d_{Cu} = 30$ Å. Arrows with black and white heads indicate magnetization direction in different Co layers. White arrows indicate the direction of an applied field. $\mu_0 H = -11.2$ mT (a), -16.0 (b), 11.3 (c), 12.4 (d), 13.9 (e), 15.7 (f). All images are of the same area in the same sample orientation.

alternating layers. For example, the walls lying in odd layers could form the DW-I, while the walls occupying even layers condense into the DW-II. Alternatively, the magnetic moments in a large number of *successive* layers could cooperate to produce an inhomogeneous spin behaviour, similar to what has been observed in a bilayer, trilayer, etc. Here, we do not discuss a reason for that behavior. Note, however, that the orientation of teeth of DWs-I and II as well as the change in the magneto-optic contrast at the film edges and defects allows one to roughly determine the orientation of the magnetization in the different layers. A weak change in contrast at the film edges indicates that the magnetization process described above is related to the partial reversal as compared to the multilayer thickness. It is necessary to stress that noncollinear spin configurations appear in this superlattice, and the domain wall behavior is governed by spin reorientation phase transitions in a superlattice. We believe that noncollinear spins are responsible for the GMR phenomenon observed in the superlattices having thick Cu spacers.

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