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Letter to the Editor

Current-in-plane giant magnetoresistance: The effect of interface roughness and spin-depolarization due to the proximity of a buffer layer

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Abstract

We report on proximity effects of a Au buffer layer on the current-in-plane giant magnetoresistance effect (CIP-GMR) in high-quality, epitaxial Fe/Cr/Fe(001) trilayers. The lower Fe layer is grown in the shape of a wedge and allows simultaneous preparation of 24 GMR stripe-elements with different lower Fe thicknesses in the range from 13 to 14.5 ML. The layer-by-layer growth mode in combination with the small thickness variation gives rise to: (i) well-controlled roughness changes from stripe to stripe as confirmed by reflection high-energy electron diffraction (RHEED), and (ii) to a varying influence of the underlying Au buffer. The oscillatory roughness variation along the wedge yields an oscillatory GMR behavior as a function of Fe thickness and confirms the previous result that slightly increased interface roughness causes a higher GMR ratio. The proximity of the Au buffer to the GMR trilayer results in an increase of the GMR ratio with increasing Fe thickness. The latter effect is explained by spin-depolarization at the Fe/Au interface and in the bulk of the Au buffer.

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Keywords: GMR; Interface roughness; Spin polarization; Proximity effect; Low-energy electron diffraction (LEED) and reflection high-energy electron diffraction (RHEED); RHEED oscillations

1. Introduction

Giant magnetoresistance (GMR) in layered magnetic structures refers to an increase of the electrical resistance when the alignment of the magnetizations in adjacent ferromagnetic layers, which are separated by non-magnetic interlayers, changes from parallel to antiparallel. For currents flowing in the sample plane (CIP-geometry), it is interpreted as due to spin-dependent electron scattering at the interfaces or in the bulk of the ferromagnetic films [1]. Hence, lattice defects, interface roughness, intermixing at interfaces, etc., all related also to sample quality, should have an important effect on GMR, but it is difficult to trace the origin of an enhanced or attenuated GMR back to some particular source. In an attempt to compare GMR in samples, which differ only with respect to interface roughness, but are otherwise as much alike as possible, we have exploited the fact [2] that in layer-by-layer growth, obtained in MBE, the growth front produces alternately a smooth surface when the last monolayer (ML) is nominally filled and the most rough one when nominally half filled. This shows up in intensity oscillations in reflection high-energy electron diffraction (RHEED) as documented by numerous related studies [3]. We have previously reported an increase of GMR in Fe/Cr/Fe(0 0 1) structures grown on Au buffers, which was uniquely related to an increased roughness at the Fe/Cr interfaces [2]. However, only two samples with different degrees of roughness have been compared. In order to make this study more substantial and to demonstrate reproducibility, we want to show here the relation between interface roughness and GMR in a

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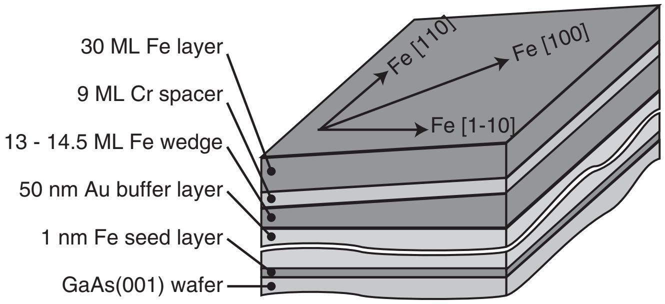
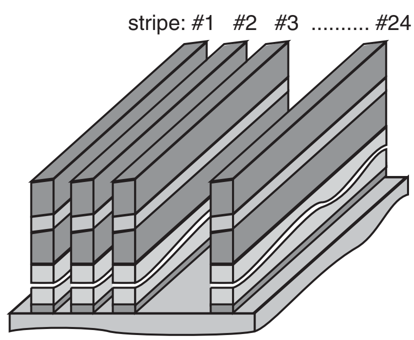


(a)



(b)

Fig. 1. Layer sequence (a) and schematic layout (b) of the conducting stripes after structuring for a single-wedge sample. The lower Fe film has increasing thickness from left to right ("wedge"). For double-wedge samples, the upper Fe film is also wedge-shaped with an opposite slope (see Fig. 2f).

whole range of interlayer thicknesses and the related RHEED oscillations.

Furthermore, a decrease of GMR with decreasing thickness of the Fe film adjacent to the Au buffer is observed and attributed to the attenuation of GMR due to spin depolarization induced by the proximity of the Au buffer.

2. Sample preparation

A sketch of our sample structure is shown in Fig. 1. Details on the growth have been described elsewhere [2]. The Au buffer layer is necessary to obtain sufficiently good sample quality to enable the observation of RHEED oscillations (step-flow growth leading to even higher sample quality but suppressing RHEED oscillations would not serve our purpose). The big disadvantage of the buffer, viz. shunting of the current and thus reducing strongly the GMR signal, cannot be avoided. We obtain a good compromise by deposition of an Au(0 0 1) buffer of 50 nm thickness. The buffer is grown at 100 °C and the subsequent Fe/Cr/Fe(0 0 1) structure at ambient temperature. The lower Fe film is prepared in the form of a wedge (13–14.5 ML thick) by shifting the substrate slowly behind a shutter during the evaporation of the last 1.5 ML of the Fe. The surface of the wedge displays the desired variations of the roughness. After deposition of the various layers, the sample is laterally structured by optical lithography and ion-beam etching. The pattern for the GMR measurements consists of 24 stripes as indicated in Fig. 1b, which are mutually electrically isolated to allow CIP-GMR measurement on each individual stripe. The stripes are about 8 mm long and only 50 μm wide, such that the thickness variation due to the wedge slope within a single stripe can be neglected.

3. Observation of RHEED intensity oscillations

Fig. 2a displays the RHEED signal during the growth of the first 13 ML of the lower Fe film, i.e. before the final growth of a wedge. Since the deposition was stopped at a RHEED intensity maximum, the film surface is nominally smooth. Further Fe was now evaporated during which the substrate was slowly moved behind a shutter, thus resulting in a wedge with a thickness increase of approximately 1.5 ML over a total lateral length of 8 mm. The roughness at the surface of the wedge was characterized after finishing the deposition by monitoring the RHEED intensity while the electron beam was scanned along the wedge. The result of both forward and backward scans is shown in Fig. 2b.

The next step is the growth of 9 ML of Cr. RHEED oscillations from the surface of the Cr film obtained during its preparation, are shown in Fig. 2c. The vertical arrow in Fig. 2b indicates the spot, at which the electron beam hit the sample and the signal was monitored. We have chosen a position, where the underlying Fe wedge displays the largest smoothness, and thus the oscillation in Fig. 2b starts at a maximum. A lateral scan from the Cr surface along the wedge direction recorded after finishing the Cr deposition is displayed in Fig. 2d. Comparing it with Fig. 2b, we find that the roughness distribution on the Cr spacer layer essentially reproduces the one of the surface of the underlying wedge-shaped Fe film. We complete the stack by the preparation of the upper Fe film of 30 ML thickness. Fig. 2e displays the RHEED oscillations taken during growth at the spot indicated by the vertical arrows in Figs. 2b and d. In summary, we have characterized the sample for the measurement of the effect of interface roughness on the GMR by the observation of RHEED intensity oscillations for each individual layer. Figs. 2b and d give the roughness distribution along the wedge for both interfaces of the Cr interlayer with the lower and upper Fe layer, respectively.

So far, we have described the preparation of the single-wedge samples. We also prepared double wedges, where the upper Fe film is also in the form of a wedge but with the opposite slope. Therefore, the thickness variations of the two wedges compensate each other (see inset of Fig. 2f). We show a position scan of the electron beam for a double-wedge sample taken after the preparation of the upper Fe wedge, but before depositing the 30-ML-thick, flat part of the upper Fe layer in Fig. 2f. As expected, the RHEED intensity is high and does not vary along the wedge.