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STRUCTURAL STUDIES OF Co/Cu AND Co/Ru INTERFACES USING ^{59}Co NMR METHOD

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The structural and magnetic properties of three magnetron sputtered multilayers at the 2nd maximum of antiferromagnetic coupling were studied using ^{59}Co NMR spectroscopy: [Co(20 Å)/Cu(20 Å)]$_{20}$, [Co(20 Å)/Ru(18 Å)]$_{20}$ and a heterostructure, in which non-magnetic spacers alternated between Cu and Ru. Co/Cu interfaces were found to be relatively sharp, extended over 3 monolayers, while the Co/Ru interfaces extend over 6 monolayers due to the good miscibility of Co and Ru. The NMR restoring field in the heterostructure is found to be the average of the restoring fields in both reference samples.

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Co/Ru multilayers display one of the strongest antiferromagnetic (AF) coupling ever reported in a multilayer system [1]. In spite of that, the giant magnetoresistance (GMR) effect is very low in these materials, which has been attributed to a considerable interdiffusion of interfaces [2], or to a small difference between the spin-polarized density of states at the Fermi level [3]. With the aim to improve the magnetotransport properties — GMR higher with respect to Co/Ru multilayers and magnetoresistive hysteresis smaller than that observed in Co/Cu multilayers at 2nd maximum of antiferromagnetic coupling (2nd AFM) — we have prepared a heterostructure with the following layer sequence: [Co(20 Å)/Ru(19 Å)/Co(20 Å)/Cu(21 Å)]$_{10}$, grown on 100 Å Ru buffer. The GMR effect that we have measured in this heterostructure is 5 times higher that that observed in the corresponding Co/Ru multilayer. Its absolute value (1.5%) is, however, still too low to be considered for practical applications and about 10 times lower than GMR exhibited by Co/Cu multilayers. Compared to Co/Cu multilayers at the 2nd AFM, the heterostructure displays reduced magnetoresistive hysteresis. Also, the saturation field is reduced about twice with respect to the Co/Ru multilayer. In order to elucidate mechanisms responsible for the observed magneto-transport properties we have carried out a detailed structural study in

the heterostructure as well as in the reference Co/Cu and Co/Ru multilayers using ^{59}Co NMR technique.

Figure 1a presents the NMR spectra recorded at 4.2 K from the 3 studied samples. All three spectra have the intensity pattern typical of multilayers of Co and a non-magnetic spacer: a main peak, at the frequency above 200 MHz, corresponding to Co atoms inside the Co layer and the tails to lower frequencies characteristic of interface of Co with the non-magnetic elements. The Co/Cu multilayer displays a strong Co peak at 215 MHz, indicating the presence of a clearly defined Co layer with a slightly strained fcc structure. In contrast to that, the intensity of Co peak in both Ru containing multilayers is heavily suppressed and the line around the Co frequency is very broad. This indicates the lack of a well defined texture and the presence of stacking faults that generate locally either hcp or fcc structures. A clear shift towards a lower frequency observed in the heterostructure when compared to the Co/Ru multilayer means that the preference for Co stacking has changed from hcp to fcc. This is expected since Cu imposes its fcc structure in the interface alloy.

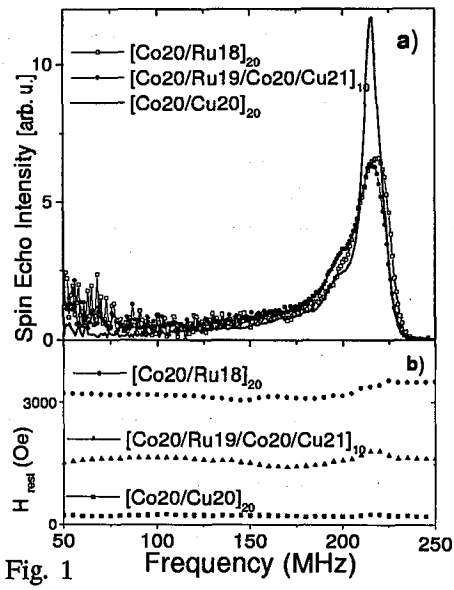

Fig. 1

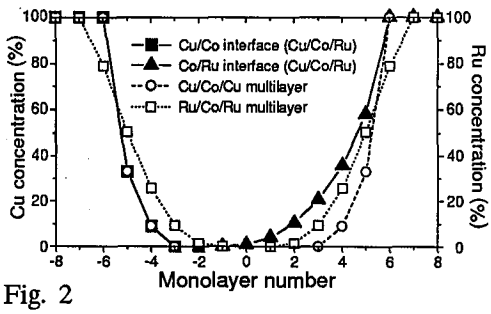

Fig. 2

Fig. 1. (a) ^{59}Co NMR recorded at 4.2 K from the studied samples, (b) NMR restoring field obtained at each frequency point using procedures described in Refs. [4, 5].
Fig. 2. Impurity concentration profiles in the interfaces calculated in frames of the diffuse interface model.

Figure 1b presents the restoring field acting on the nuclear magnetization, which is directly linked to any interaction responsible for sample's magnetic stiffness such as coercivity or exchange coupling between the magnetic layers [4]. In a heterostructure it is almost exactly the average of restoring fields observed in the reference Co/Ru and Co/Cu multilayers. We have already shown that in case

of 2nd AFM samples the restoring field is determined by the strengths of antiferromagnetic coupling between magnetic layers [5]. It can thus be concluded that the magnitude of effective AF coupling in the heterostructure is the average of the coupling strength in the two reference multilayers which means that the individual exchange interactions through the non-magnetic Cu and Ru spacer retain their strength. This fact can be used to tailor desired properties of multilayers. We speculate that the approximately twice smaller saturation field observed for the heterostructure than that observed for the Co/Ru film may be a consequence of the lower effective exchange interaction acting on the Co layers.

The procedures used to fit the spectra to interface models have been elaborated [6]. They make use of the fact that local hyperfine field, observed in the NMR experiment is sensitive to the local atomic arrangement. In the samples studied, a simple model of diffuse interface has been applied, since the experimental spectra display a structureless and extended intensity in the part attributed to the interface. In this model each atomic layer in the interface consists of a two-dimensional random alloy of Co and the corresponding second element. Alloy concentration varies monotonically from one layer to another. The fitting parameters are the number of interface layers and alien atom concentration in each atomic layer. As a result, one obtains the extent of the interface and its concentration profile.

Figure 2 shows the concentration profiles in each of the studied reference samples using the above procedure. In case of Co/Cu multilayer the interface extends over 3 monolayers and contains the amount of Co equivalent to 5 Å of deposited thickness [7]. In contrast to this, Co/Ru interface extends over 6 monolayers and contains the amount of Co equivalent to 9 Å thick Co layer. The modeling revealed that only a residual Co layer exists in this multilayer, comprising of only 1 atomic layer. Therefore its structure is not well defined even though its fitted frequency is in the hcp frequency range. In case of the heterostructure a linear combination of the concentration profiles obtained in the two reference samples was not effective to fit the experimental spectrum, indicating some kind of structural modification. Different fitting attempts have shown that in order to accommodate for the observed differences, a very strong modification of the Co/Cu interface would be required. This solution seems non-physical since it requires the entire microstructure of the Co layer to be changed. Alternatively, if one allows the Co/Ru to vary, keeping the Co/Cu interface fixed, only slight modification of this already heavily intermixed interface is required. We have opted for this latter solution, since it is more natural to assume that Co and Ru — easy mixers — will intermix a bit further and not to expect the difficult mixers, such as Co and Cu to develop an extended alloy. A good fit in case of heterostructure was obtained using the concentration profiles shown in Fig. 2: Co/Cu retains its relatively sharp concentration profile observed in the reference multilayer and Co/Ru interface is intermixed even deeper. Also in this case the bulk of Co layer is limited to one Co layer only and its frequency is shifted to the fcc range.

In conclusion, the performed analysis of NMR data obtained from the 3 studied samples strongly confirms the expectation that in case of the Cu/Co/Ru heterostructure the individual features, such as the strength of exchange coupling and the interface concentration profile are retained with respect to the reference

Co/Cu and Co/Ru multilayers. However, our attempt to improve the GMR properties with respect to Co/Ru multilayers was only partly successful, most probably due to the persisting strong intermixing in the Co/Ru interface area.

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