Influence of Ni thickness on oscillation coupling in Cu/Ni multilayers

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Abstract: The results of investigation of magnetic properties of [Cu/Ni]x100 were presented. Samples were deposited by face-to-face sputtering method onto the silicon substrate, the thickness of Cu layer was constant (d_{Cu} = 2 nm) and the thickness of Ni layer – variable (1 nm ≤ d_{Ni} ≤ 6 nm). In Cu/Ni multilayers, for the thickness of Ni layer bigger than 2 nm antiferromagnetic coupling (A-F) were observed, for the thickness of Ni smaller than 2 nm A-F coupling is absent.

1. Introduction
Grüenberg [1] discovered antiferromagnetic coupling in multilayers Fe/Cr. Later Parkin [2] proved that in this type of systems, but with changed thickness of spacer Cr interlayer exchange coupling was presented, for example in NiFe/Cu [3] and NiFe/Ag [4]. The analysis of their presented results in works [1-4] showed that the size of exchange coupling is influenced not only by the thickness, but the type of spacer as well. It was shown in [5] that the thickness of ferromagnetic layer caused the change in the exchange coupling. The aim of this work was the investigation of the influence the ferromagnetic Ni layer thickness on character of coupling in Cu/Ni multilayers.

2. Experimental
The systems Cu/Ni were deposited onto the silicon substrate using face-to-face sputtering method. The thickness of Cu layer was constant (d_{Cu} = 2 nm) and the thickness of Ni layer was variable (1 nm ≤ d_{Ni} ≤ 6 nm). The velocity of deposition for Cu was 45.4 Å/min, for Ni layer – 34.4 Å/min. The structural characterization of Cu/Ni multilayers was performed by X-ray high-resolution X’Pert (Philips) diffractometer with CuKα radiation in Θ-2Θ geometry. The room temperature hysteresis loops of Cu/Ni multilayers were obtained from the measurements by vibrating sample magnetometer (VSM). This curves for a 100x[Cu/Ni] systems were measured in the external magnetic fields up to 800 kA/m, for parallel direction to the film plane (easy axis).

3. Results and discussion
The X-ray diffraction pattern for multilayered systems 100x[Cu/Ni] was presented in Fig 1. Both peaks from plane Cu, Ni and satellite peaks were visible. The presence of satellite peaks gives information about periodic structure of sample. The positions of satellite peaks allow to determine the period of multilayered system using the equation [6]:

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\[ \Lambda = \frac{(m-n)\lambda}{2(\sin \theta_m - \sin \theta_n)} \]  

where:

- \( \theta_m, \theta_n \) - the m-th and n-th position of satellite peak,
- \( \lambda \) - the length of wave of radiation used for investigation.

The value of the system period calculated from X-ray diffraction (\( \Lambda \approx 44 \text{ nm} \)) corresponds well to the theoretical value of 100x[Cu/Ni] period.

The analysis of the shape hysteresis loops measured in easy axis of investigated samples gives the information about the nature antiferromagnetic coupling (A-F).

The field dependences of magnetization for samples with variable thickness of ferromagnetic layer were presented in Fig.2.

The dependence of magnetization curve as a function of the magnetic field for samples with thickness \( d_{\text{Ni}} = 1 \text{ nm} \), and \( d_{\text{Cu}} = 2 \text{ nm} \) is linear, this is characteristic for diamagnetics.

The shape of hysteresis loops obtained for samples with the thickness of ferromagnetic layer \( d_{\text{Ni}} = 1.4 \text{ nm} \); \( 1.5 \text{ nm} \); \( 1.6 \text{ nm} \) and \( d_{\text{Cu}} = 2 \text{ nm} \) and the saturation field \( H_s \) which is about \( \pm 10 \text{ kA/m} \) indicate antiferromagnetic coupling A-F II (the second antiferromagnetic maximum \([7]\)). Additionally, in this case the remanent magnetization is equal zero. Moreover, the saturation field depends on the thickness of ferromagnetic layer Ni. The dependence of saturation field on the thickness of Ni layer for samples with A-F coupling was presented in Fig. 3.
Fig. 2. The field dependences of magnetization for multilayers 100×[Cu(2 nm)/Ni(d)] for different thickness of ferromagnetic layer (d).

Fig. 3. The saturation field ($H_s$) vs. the thickness of Ni layer for multilayered 100×[Cu/Ni]

The value of saturation field decreased with the thickness of Ni layer. According to [8] the oscillation of the coupling energy ($J_{AF}$) is directly proportional to the saturation field. For the thickness $d_{Ni} = 1.4$ nm; 1.5 nm; 1.6 nm the coupling energy equal $J_{AF} = -0.1 \times 10^{-9}$ J/m².
This value of $J_{AF}$ is much smaller (three orders of magnitude) than the value for 100x[NIFe/Cu] \[3\]. The magnetic hysteresis loops for the thickness of Ni layer 2 nm and 2.5 nm showed partially ferro- and antiferromagnetic coupling in Ni films ($0<M_R<M_S$) (Fig.1). However, ferromagnetic coupling of Ni films (F-F) was obtained for the thickness of Ni equal: 3 nm; 4 nm and 6 nm (Fig.1). This hysteresis loops for F-F coupled samples are characterised by the coercivity field ($H_C$), but the saturation magnetization is almost equal the remanent magnetization ($M_S=M_R$) (Fig.4). The saturation magnetization as a function of the thickness of ferromagnetic layer was presented in Fig. 5. The increase of Ni thickness effected resulted in the increase of the saturation magnetization for multilayers.

Fig.4. Dependences of coercivity and remanent magnetization vs. thickness of Ni layer for multilayered systems 100x[Cu/Ni]

1.6 nm (because the thickness of Cu spacer 2 nm [8]), for their thickness $F_{AF} = 1$.

Fig. 5. Saturation magnetization vs. Ni layer thickness for multilayered systems 100x[Cu/Ni]
Fig. 6. $F_{AF}$ vs. Ni layer thickness for multilayers 100x[Cu/Ni]

4. Conclusion
Multilayered systems 100x[Cu/Ni] obtained by face-to-face sputtering method with constant thickness of Cu (2 nm) and variable thickness of Ni ($1 \text{ nm} \leq d_{\text{Ni}} \leq 6 \text{ nm}$) were investigated. The magnetic measurements were out in the external magnetic field parallel to the surface of multilayers (easy axis). The analysis of the shape of magnetization curves in function of the external magnetic field showed that for multilayers:
1)Cu(2 nm)/Ni(1 nm) – the M(H) dependence is linear, which is characteristic for diamagnetics;
2)Cu(2 nm)/Ni(1,4; 1,5; 1,6 nm) – the hysteresis loops for samples antiferromagnetically coupled (A-F II);
3)Cu(2 nm)/Ni(2; 2,5 nm) - partially ferro- and antiferromagnetically coupled Ni films
4)Cu(2 nm)/Ni(3; 4; 6 nm) – the magnetic hysteresis loops for ferromagnetically coupled Ni layers.
Comparison of values of the coupling energy of the second antiferromagnetic maximum obtained for 100x[Cu/Ni] with values for 100x[NiFe/Cu] [3] confirmed that the type of ferromagnetic layer influence the magnitude of exchange coupling.

Acknowledgements
The authors are grateful to Doctor B. Szymański from the Institute of Molecular Physics of the PAS in Poznań for supplying the sputtering multilayerd systems Cu/Ni.

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