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Phase shift of exchange coupling oscilations in magnetic multilayers

V.M. Uzdin[a,*], N.S. Yartseva[b], L. Adamowicz[c]

[a]*Institut für Angewandie Physik, Heinrich-Heine-Universität Düsseldorf, D-40225, Düsseldorf, Germany*
[b]*Institute of Metal Physics, GSP-170, Ekaterinburg, 620219, Russia*
[c]*Warsaw University of Technology, Institute of Physics, Koszykowa 75, 00-662 WarszawaPoland*

Abstract

The origin of phase shifts in the oscillatory behaviour of exchange coupling (EC) of Co/Ru/CO and Co/Cu/Co trillayers with an addition of Ag impurities into the Co layer is explained within the framework of a quantum-well (QW) model. It is shown that Ag impurities induce the shift of the Fermi level relative to the bottom of the band and allow the observation of short-range oscillations of the EC. This is in contrast to the studies involving the increase of the layer thickness where only the long-range period is observed due to "aliasing" effect. On the basis of the simplified infinite QW-theory the difference between phase shift in symmetrical and asymmetrical trilayers is analysed. © 1999 Elsevier Science B.V. All rights reserved.

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Exchange coupling (EC) in metallic magnetic superlattices has been investigated quite intensively in the last years. Previously, most of the studies were focussed on the dependence of the period of the coupling oscillations on the properties of the nonmagnetic spacer, but recently the dependence of the phase and strength of the oscillations and their connection with the magnetic layer constitution is attracting large interest. Experimental investigations of these dependencies demands very careful sample preparation and control of the interface roughness, which can mask true trends. Quantitative theoretical descriptions have to take into account the real band structure of the magnetic and the nonmagnetic layers as well as the interface region. In Ref. [1] the phase shift in the oscillatory interlayer EC across the Cu layers in Co/Cu, Co_{50} Ni_{50}/Cu, Ni/Cu, Ni_{40} Fe_{60}/Cu multilayers was investigated. It was shown that the phase of the EC oscillations is sensitive to the position of the Fermi level relative to the band gaps, which exist in the band structure of magnetic layers. Such gaps lead to the partial confinement of electrons with appropriate spin projection in the quantum wells (QW) formed by the magnetic layers. Observation of a very strong change in the phase (upto 360°) in Co/Ru/Co and Co/Cu/Co trilayer systems has been reported in Ref. [2]. The phase was modified by the addition of a small amount (up to 8%) of Ag to the Co layer. Again, interpretation of the experiments was based on the idea of the shift of Fermi level and the change of the depth of QW under the influence of Ag impurities. However, the explanation of such a large phase shift and essential differences observed for trilayers with Ru and Cu spacers was given in Ref. [2] on a qualitiative level only.

Here we put forward the simplified theory based on infinite QW model [3,4], which can clarify some of the dependencies observed in Ref. [2]. We consider the case, when ferromagnetic/nonmagnetic (*FM*/*NM*) interface represents a quantum barrier for itinerant electrons with

* Corresponding author. Tel.: + 49-211-81-12284; fax: + 49-211-81-13658.
E-mail address: uzdin@uni-duesseldorf.de (V.M. Uzdin)

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spin projection in the direction of magnetisation in the *FM* layer (similar to the Co/Cu multilayers [5]). A set of QW for ferromagnetic (FM) and antiferromagnetic (AF) ordering of the magnetic layers in *FM/NM/FM* sandwich is shown in Fig. 1a. For the calculation of EC it is necessary to find the difference $\Delta\Omega$ between thermodynamic potentials Ω for the itinerant electrons in the QW, formed by FM and AF coupled magnetic layers $\Delta\Omega = \Omega^{AF} - \Omega^{FM}$. As it was in Ref. [3] that the main contribution, which determines, as a rule, the sign of EC parameter ***J***, arises from the electrons confined in the narrowestQW (with thickness L_0 on Fig. 1a). *J* oscillation with thickness L_0, but in the framework of the free electron model the period of oscillation, which is governed by the dimensionless parameter $k_F L_0$ ($k_F = (2m\varepsilon_F)^{1/2}$ is the Fermi momentum without transverse quantization), appears to be rather short: of the order of de Broglie wave-length of electrons. One of the ways to overcome the discrepancy between the calculated small period (about 2 Å) and the long period (about 10 Å) observed in

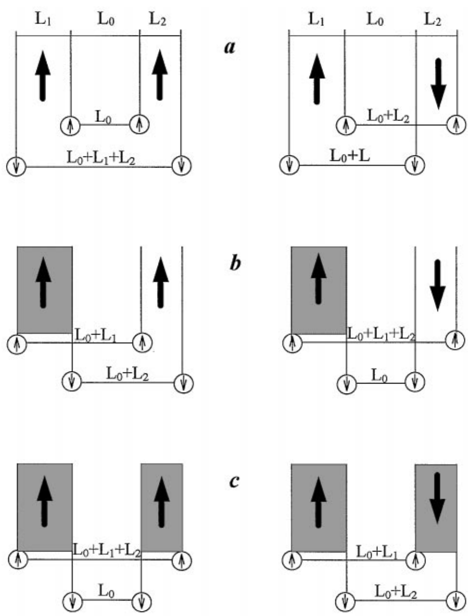

Fig. 1. QWs for FM and AF ordering in trilayers. L_0, L_1, and L_2 are thickness of nonmagnetic spacer, left and right magnetic layers, respectively. (a) Without Ag doping. L_0 and $L_0 + L_1 + L_2$ are the QW widths for the electrons with "spin-up" and "spin-down", respectively, in the case of the FM coupling, $L_0 + L_2$ and $L_0 + L_1$ are the QW widths in the AF case, correspondingly. (b) With Ag in the left magnetic layer. $L_0 + L_1$ and $L_0 + L_2$ are the QW widths for the electrons with "spin-up" and "spin-up", respectively, for the FM ordering in trillayer; $L_0 + L_1 + L_2$ and L_0 are the QW widths for the AF ordering. (c) With Ag in both of the magnetic layers. $L_0 + L_1 + L_2$ and L_0 are the QW widths for the electrons with "spin-up" and "spin-down", respectively, for the FM ordering in trilayer; $L_0 + L_1$ and $L_0 + L_2$ are the QW widths for the AF case.

the experiment, is to take into account the noncommensurability of the electron wavelength λ and lattice constant *l*. The real change of the layer thickness in trilayer system can only occur by descrete values which are a multiple of the lattice constant. As a result, the observed oscillations period appears to be much larger than λ. The addition of a small amount of Ag in magnetic layer leads to the shift of the Fermi level and, consequently k_F. Estimatins reported in Ref. [2] for 6.25% Ag in bulk Co predict a shift of the Fermi level by 0.32 eV. As k_F enters the formula for $\Delta\Omega$ (through the number of transverse movement quantum levels below Fermi level) together with the well width *L* [3], one can consider that doping by the Ag atoms is equivalent (from the point of view of EC behaviour) to a smooth change of QW width. The later thereby manifests the short-range oscillations and, consequently the rapid change of the phase of the coupling with variation of the Ag concentration. It should be noted, however, that the value of phase shift $\Delta\varphi = \Delta k_F L = 0.5(\Delta\varepsilon_F/\varepsilon_F) k_F L$ for relatively small spacer width *L* (of the order of 15–20 Å) appears to be less than that observed in the experiment.

It is obvious, that for the quantitative description of the experiment, the details of the band structure of the elements constituting the sandwich and the interface roughness have to be taken into account. Calculations within the free-electron model [6] shows that the change of the QW depth can lead to additional shifts of the phase of EC. To model the interface roughness we performed the calculation of EC for different QW shapes. In particular, for the trapezoidal QW with different slope of the walls we obtained the same period of oscillations but the phase was shifted significantly.

Consider now the experimental results concerning difference in the behaviour of Co/Ru and Co/Cu multilayers with Ag doping. The phase shift in Co/Ru trilayers appears to be more than 3 times larger than for the Co/Cu system. In Ref. [2] it was explained by a large density of d-states near Fermi-level for the bulk Ru. Note, however, that in the experiment described in Ref. [2] for Co/Ru/Co trilayers only one magnetic layer was doped with Ag, whereas for Co/Cu/Co Ag was introduced in both Co layers, so that the CoAg/Cu/CoAg system stayed symmetric. Doping with Ag can lead to the appearance or disappearance of band gaps in the band structure of Co at the Fermi level. Consider the case when the band gap disappears for "spin-up" electrons and arises for "spin-down" as shown in Fig. 1b and Fig. 1c. Now the barrier at the AgCo/NM interface will exist for "spin-down" electrons whereas at Co/NM it exists for "spin-up" electrons. The structures of the QWs for symmetric and asymmetric Ag doping, are shown in Fig. 1b and c, respectively. Doped layers are shown by grey color. The sets of wells on Fig. 1c and a coincide for FM and AF coupled trilayers. Consequently, the shift of the EC phase will be relatively small. The structure of wells on Fig. 1b is rather different. Here the FM and AF coupled magnetic layers interchange their positions. The result for the structure shown in Fig. 1b will produce a shift in the phase of the oscillation for EC up to 180° realtive to the case shown in Fig. 1a. Of course, details of the real-band structure will certainly change this much simplified picture, but nevertheless a strong enhancement of phase shift for the asymmetric Co/Cu trilayers would be predicted.

In summary, we consider different mechanisms which can be responsible for the large shift of the phase of the oscillation of the EC observed experimentally in Co/Ru/Co and Co/Cu/Co trilayers with Ag doping in Co layers. We predict an enhancement of the effect for asymmetric Co/Cu systems.

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