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External Magnetic Field Influence on Exchange Coupling Oscillations in Ultrathin Fe/Au/Tb Film Structures

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In the present work exchange coupling between ultrathin Fe (8 Å) and Tb (12 Å) layers separated by Au spacer of varied thickness (3~20 Å) was studied. Anomalous Hall effect measurements showed weakly damped oscillating dependence of the Hall conductivity as a function of Au spacer thickness. Disagreement of the observed damping with the RKKY model of interlayer exchange coupling was explained by the influence of external magnetic field on the behaviour of exchange coupling oscillations. It was confirmed by Hall-like effect measurements at zero applied magnetic field and also illustrated by corresponding estimations.

1. Introduction

When two ferromagnetic films are separated by a non-magnetic spacer layer, the magnetizations of the layers are coupled to each other by an exchange interaction through conduction electrons of the spacer layer. As the thickness of the spacer layer is varied, the coupling can oscillate in sign. Exchange coupling through a non-magnetic spacer in rare-earth (RE) based structures Gd/Y was first observed by Kwo *et al.* [1] and Majkrzak *et al.* [2]. Similar interlayer exchange coupling was also observed for a large variety of mostly transition metals (TM) across various non-magnetic spacers (see i.e. Grünberg *et al.* [3] and Parkin [4]). As the magnetic moment of the most of RE atoms is $7 \div 10\ \mu_B$ then the use of RE metal as one of magnetic layers in multilayer structure can result in considerable increase of the net magnetic moment of all system in the case of the parallel orientation of RE and TM magnetic sublattices. Such multilayer film structures can become the film analogue for permanent magnets, which can be applied in elements of MRAM, magnetic tunnel junctions, etc.

The interpretation of experimental observations are provided by methods based on the RKKY interaction model adapted to the multilayer geometry due to Bruno and Chappert [5]. According to this model exchange coupling oscillations decay as z^{-2}, where z is the thickness of non-magnetic spacer between two ferromagnetic layers. Exchange coupling between RE (Tb) and TM (Fe) through various non-magnetic spacers was first studied by Hoffman and Scherschlicht [6]. But experimental results obtained by these authors did not agree with the RKKY model. They have observed oscillation of the net magnetic moment of the investigated structures with the increase of spacer thickness. But this oscillation did not show change of sign and its amplitude was increasing. As studies in [6] were carried out on multilayered structures it introduced an ambiguity in understanding the nature of the exchange coupling. It happens because in such structures the exchange coupling between the neighboring magnetic layers is influenced by the coupling with distant layers. That is why the investigation of the exchange coupling in trilayer film structures is important.

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2. Experiment

Exchange coupling between ultrathin Fe (8 Å) and Tb (12 Å) layers separated by Au spacer of varied thickness (z_{Au} = 3~20 Å) was studied. Film samples were prepared on Si substrates by electron-beam evaporation in an ultrahigh vacuum system with the background pressure of ~10^{-9} Torr. Evaporation rates were about $0.1 \div 0.4$ Å/s and were controlled by quartz microbalance.

To characterize film samples magnetically we used anomalous Hall effect (AHE) measurements, which are able to provide sufficiently accurate picture of the magnetic state of the coupled layers.

3. Results and Discussion

AHE studies of trilayer Fe/Au/Tb structure [7] showed the periodical change of the value and sign of the Hall resistivity with the increase of z_{Au} (Fig. 1a). This indicates a periodical change of the sign of exchange interactions between Fe and Tb layers as it is predicted by RKKY model [5]:

$$J(z) = -J_0 \sum_{\alpha} \frac{d^2}{z^2} A_{\alpha} \sin(q_S^{\alpha} z + \phi_{\alpha}), \quad (1)$$

where $z = (N + 1)\cdot d$ is the distance between two magnetic layers, d is the interlayer spacing, N is number of atomic layers of the spacer, A is an amplitude, q_S are wave vectors linking two points $\mathbf{k}_1$ and $\mathbf{k}_2$ of the spacer Fermi surface with antiparallel velocities, and ϕ is a phase shift related to the topology of the Fermi surface at $\mathbf{k}_1$ and $\mathbf{k}_2$.

But comparison of the experimental results with calculations (Fig. 1c) using Eq. (1) [8] indicate weak decay of the exchange coupling in the investigated trilayer structure with the increase of z_{Au} (Fig. 1b). It was proposed that exchange processes in such structures can be influenced by external magnetic field. As is well known all conventional techniques used for investigation of magnetic properties of magnetic materials (magneto-optic, magneto-transport, magneto-resonance) suppose application of an external magnetic field. That is why investigation of the behaviour of the exchange coupling at zero applied magnetic field is of particular interest. This can be realized if we use theoretical studies of Hirsch [9, 10] who predicted appearance of the Hall-like effect due to the fact that in general a spin current exists in ferromagnetic metals when a charge current exists.

Electrons carrying a spin and associated magnetic moment (m) experience a transverse force (F) when they are moving in a longitudinal electric field. If there is a net magnetization in the system there will be a magnetization current (I_m), or spin current, associated with the flow of electric current (I_x), and the transverse force will give rise to a charge imbalance in a direction perpendicular to the current flow and hence to a transverse Hall voltage (Fig. 2).

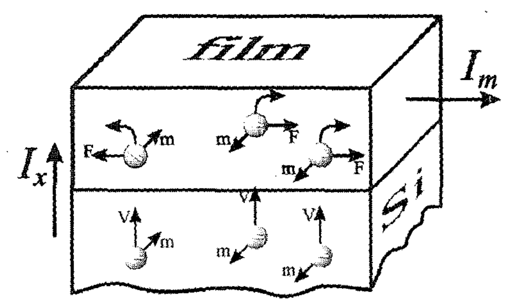

Fig. 2. Scattering of spin-polarized electrons in ferromagnetic metal.

To obtain a spin-polarized current the potential difference was applied perpendicular to the system "magnetic film/semiconductor substrate". Due to existence of Hall-like effect there appears a current in the transverse direction (i.e. in the film plane). As a result the dependence of measured transverse current I_m on z_{Au} was obtained for certain values of applied potential difference (Fig. 3). If we compare this experimental dependency with calculations then one can mention good agreement of its behaviour with the RKKY model. Weak decay of AHE oscillations in comparison with results of Hall-like effect may be connected with the influence of external magnetic field, applied during AHE measurements, on exchange coupling oscillations.

Interlayer exchange coupling in trilayer structures can be considered in the framework of the quantum well

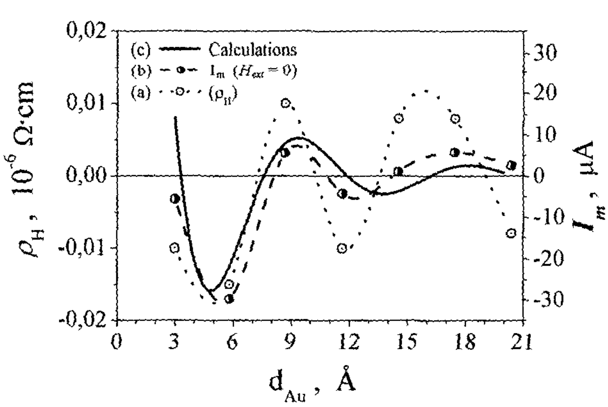

Fig. 1. Exchange coupling in trilayer Fe/Au/Tb structure as a function of z_{Au}. (a) AHE measurement results [7]; (b) Hall-like effect at zero applied magnetic field; (c) calculated curve [8].

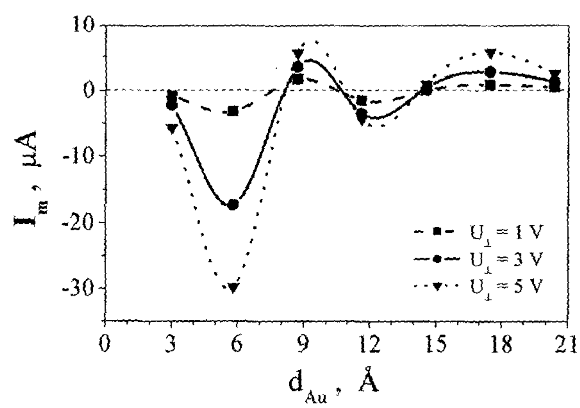

Fig. 3. Oscillations of the transverse current I_m as a function of Au spacer thickness (z_{Au}).

model [11], in which interfaces between the spacer and adjacent magnetic layers may be regarded as spin-dependent potential barriers. Multiple scattering of spin-polarized conduction electrons may give rise to quantum-well states similar to standing waves in a box. Moreover, the stronger the spin-dependent reflection, the stronger the oscillatory coupling [12]. Hence the highest amplitude of exchange coupling may be obtained in the case of specular reflections of conduction electrons from the interfaces. In [13] it was shown, that such conditions are possible in the case of electron channeling, i.e., when the electron is confined to a layer within the material as a result of the band structure. This is achieved when the magnetic moments in adjacent layers are parallel, in other words, in the case of saturation magnetization. If electron channeling exists in the Au spacers, the mean-free path of the specularly reflected electrons may be long. The number N_{sp}, of specular reflections prior to diffusive scattering at the Fe/Au interface, is determined by the potential step at the interface and does not change with Au thickness. Provided the mean-free path in the Au layer, λ_{Au}, is greater than the thickness of the Au (z_{Au}), the mean-free path is directly proportional to the product of the number of specular reflections and the Au thickness: $\lambda_{Au} \sim N_{sp} \cdot z_{Au}$. Thus with the increase of spacer thickness the damping of exchange coupling oscillations will become weaker.

So, the observed influence of external magnetic field on the exchange coupling behaviour may be illustrated if we add an appropriate multiplier in Eq. (1). This additional multiplier should include the dependence on external magnetic field, i.e., $N_s^{f(H)}$, and tend to 1 at zero external magnetic field. Presence of this multiplier should somewhat compensate the quadratic damping with the increase of spacer thickness, that is it has to be proportional to λ_{Au}. Moreover, if we consider that specular reflections of conduction electrons at interfaces are achieved under condition of complete magnetic ordering in magnetic layers, then boundary conditions for $f(H)$ will be as follows:

$$f(H) = \begin{cases} 0, \text{ if, } H_{ext} = 0 \\ 1, \text{ if, } H_{ext} = H_{sat} \end{cases} \tag{2}$$

Then equation for exchange coupling adjusted for magnetic field influence can be rewritten as follows:

$$J(z) = -J_0 \sum_{\alpha} \frac{d^2}{z^2} N_s^{f(H)} A_\alpha \sin(q_S^\alpha z + \phi_\alpha) . \tag{3}$$

As the values of Hall resistivity in AHE measurements

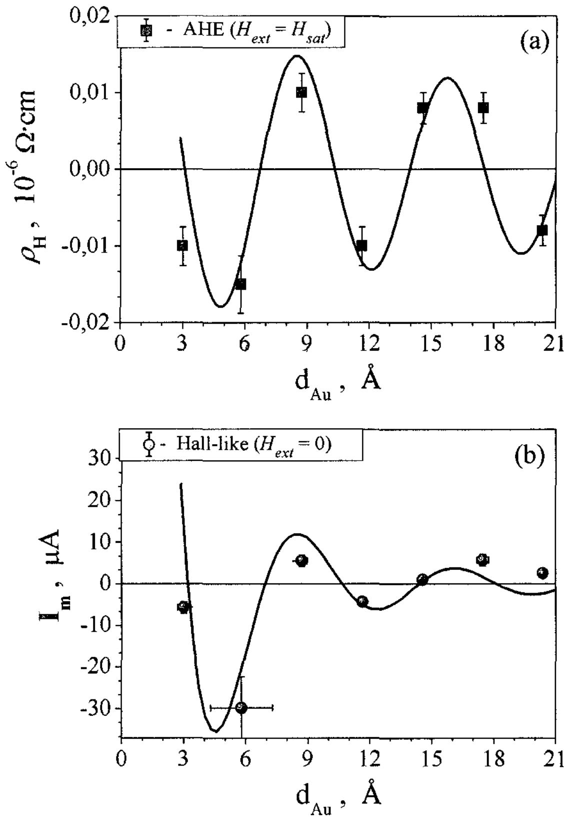

Fig. 4. Estimations of the exchange coupling behaviour in investigated trilayer film structures in the case when (a) external magnetic field is present and when (b) $H_{ext} = 0$. Dots correspond to appropriate experimental results.

were obtained at saturation field (i.e., $H_{ext} = H_{sat} \approx 600$ mT), then it is possible to make comparisons of experimental data with calculations by Eq. (3) taking in account conditions (2). As one can see from Fig. 4a such account of external magnetic field influence results in very good agreement of oscillations behaviour for calculated and experimental data. Square dots correspond to values of Hall resistivity as a function of Au spacer thickness in trilayer Fe/Au/Tb film structure on Si substrate. At the same time if $H_{ext} = 0$, the character of the oscillation damping returns to quadratic. This is well illustrated on Fig. 4b, where calculations are presented in comparison with results of Hall-like effect studies at zero applied external magnetic field (filled circles).

It should be noted that above mentioned estimations are only to illustrate the possibility of external magnetic field influence on exchange coupling in trilayer Fe/Au/Tb film structure. To obtain exact solution it is necessary to solve an appropriate problem which will include the influence of external magnetic field on exchange coupling oscillations in film structures, possibly by accounting the influence on spin-dependent reflection of spin-polarized conduction electrons from interfaces.

4. Conclusions

By means of new technique based on Hall-like effect it was shown that the behaviour of interlayer exchange coupling oscillations in trilayer Fe/Au/Tb structures is possibly influenced by the external magnetic field. It was supposed that this influence is due to change of spin-dependent reflection of spin-polarized conduction electrons at interfaces with magnetic layers that result in change of their spin-relaxation length. Estimations were made in order to take account of the magnetic field influence. Results of calculations show good agreement with experimental data for cases when magnetic field is present and when it is zero. Presented calculations are not the exact solution of exchange coupling problem accounting the influence of magnetic field, but aim to illustrate this influence.

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