Manifestation of Spin-Hall Effect in Multilayered M/N/M Film Structures

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Abstract. In the present work spin-Hall effect was for the first time experimentally utilized at room temperatures for studies of interlayer exchange coupling in ultrathin (3-40Å) M/N/M film structures at zero applied external magnetic field. Application of special technique allowed to discover the possible influence of external magnetic field on the behavior of exchange coupling oscillations. Obtained results are well explained if to take into account in the RKKY model the probable influence of magnetic field on the spin-dependent reflection coefficients of spin-polarized conduction electrons from magnetic interfaces.

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. Exchange coupling through a non-magnetic spacer in rare-earth (RE) based structures Gd/Y was first observed by Kwo \textit{et al.} \cite{1} and Majkrzak \textit{et al.} \cite{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 \textit{et al.} \cite{3} and Parkin \cite{4}). As the magnetic moment of the most of RE atoms is 7–10 \(\mu_B\) 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 using methods based on the RKKY interaction model adapted to the multilayer geometry by Bruno and Chappert \cite{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 \cite{6}. But experimental results obtained by these authors did not agree with the RKKY model. The observed oscillation of the net magnetic moment of the investigated structures with the increase of spacer thickness did not show change of sign and its amplitude was increasing. In order to clarify the nature of the exchange coupling in RE/NM/TM system it is important to study magnetic interactions in trilayer film structure.

2. Experiment
In experiment ultrathin film structures of 3-40Å thickness deposited onto Si substrates were studied.
In these trilayer M/N/M film structures magnetic (M) layers of Fe (8 Å) and Tb (12 Å) were separated by nonmagnetic (N) spacer (N = Au, Cu) of varied thickness ($z_N = 3–20$ Å). Films were fabricated by electron-beam deposition in ultrahigh vacuum system (~10^{-8}–10^{-9} Torr). To minimize interdiffusion of layers, the substrate temperature during evaporation was kept no higher than 0°C. The rates of evaporation did not exceed 0.4 Å/s and were independently controlled with quartz crystal monitors. In order to avoid formation of Fe-silicide at Fe/Si interface [7] a thin (3 Å) Au sublayer was deposited onto Si substrate. To protect from oxidation samples were capped with 30 Å Au layer. Both structural characterization (X-ray diffractometry, Auger spectroscopy) of the film structures and investigation of their functional properties were carried out. The latter were studied using traditional magnetometry methods (anomalous Hall effect and magneto-resistance measurements, polar Kerr magnetometry) as well as originally developed method based on spin-Hall effect (SHE) measurements [8]. All measurements were carried out at room temperatures.

3. Results and Discussion

AHE studies of trilayer Fe/Au/Tb structure [9] showed that the value and sign of the Hall resistivity are periodical changing with the increase of $z_{Au}$ (Figure 1a). Although Tb is paramagnetic at room temperature, the layer of Tb in trilayer structure is magnetized due to the long range magnetic interactions with Fe via non-magnetic spacer. Results of AHE studies indicate a periodical change of the sign of exchange interactions between Fe and Tb layers as it is predicted by RKKY model [5]:

$$J(z) = -J_{0} \sum_{\alpha, \beta} \frac{d_{\alpha}^{2}}{z} A_{\alpha} \sin(q_{S}^{\alpha} z + \phi_{\alpha}),$$

where $z = (N + 1)d$ 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 $k_1$ and $k_2$ of the spacer Fermi surface with antiparallel velocities, and $\phi$ is a phase shift related to the topology of the Fermi surface at $k_1$ and $k_2$.

![Figure 1. Exchange coupling in Fe/Au/Tb film structure as a function of $z_{Au}$. Inset shows the structure of thin film stack.](image1.png)

![Figure 2. Oscillations of the transverse current $I_{SH}$ as a function of Au spacer thickness ($z_{Au}$).](image2.png)

But comparison of the experimental results with calculations (Figure 1b) using Eq. (1) [10] indicated weak decay of the exchange coupling in the investigated trilayer structure with the increase of $z_{Au}$. It was proposed that exchange processes in such structures can be influenced by external magnetic field, which is usually required in all conventional measurement techniques (magneto-optic, magneto-transport, magneto-resonance). That is why investigation of the behavior of the exchange coupling at zero applied magnetic field was of particular interest. This can be realized if we use theoretical studies of Hirsch [11] who predicted appearance of the SHE due to the fact that in general a spin current exists in ferromagnetic metals when a charge current exists. To obtain a spin-polarized...
current the potential difference was applied perpendicular to the system “magnetic film / semiconductor substrate” (contacts 1 and 3 on inset of Figure 2). Size of electric contacts was ~4 mm², while the area of the sample was ~40 mm². Due to existence of SHE the current is generated in the transverse direction (i.e. in the film plane; contacts 2 and 4 on inset of Figure 2). As a result the dependence of measured transverse current $I_{SH}$ on $z_{Au}$ was obtained for certain values of applied potential difference (Figure 2). Comparing this experimental dependency (Figure 1c) with calculations (Figure 1b) one can mention good agreement of its behavior with the RKKY model [5]. Weak decay of AHE oscillations in comparison with results of SHE 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 model [12], 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 [13]. Hence the highest amplitude of exchange coupling may be obtained in the case of specular reflections of conduction electrons from the interfaces. This effect may be possible when electrons are confined to the layer within material as a result of the band structure [14], and also when all magnetic moments in magnetic layers are aligned in one direction (saturation condition). The number of specular reflections $N_{sp}$ of the electron prior to diffusive scattering at Fe/Au interface is determined by potential step at the interface and does not change with Au thickness. The mean-free path of the electron can be written as: $\lambda_{Au} \sim N_{sp} \cdot z_{Au}$. Thus with the increase of spacer thickness the exchange coupling oscillations will decay slower due to effective increase of the mean free path. So, the observed influence of external magnetic field on the exchange coupling behavior 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., $N_{s}^{(H)}$, and tend to 1 at zero 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 $\lambda_{Au}$. 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:

$$f(H) = \begin{cases} 1, & H_{ext} = 0, \\ 0, & H_{ext} = H_{sat}. \end{cases}$$

(2)

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

$$J(z) = -J_0 \sum_{\alpha} \frac{d^2}{dz^2} N_{s}^{(H)}(z) A_{\alpha} \sin(q_{\alpha} z + \phi_{\alpha}).$$

(3)

Figure 3. Estimations of the exchange coupling behavior in investigated film trilayer structure in the case when (a) external magnetic field is present and when (b) $H_{ext} = 0$. Dots correspond to appropriate experimental results.
As the values of Hall resistivity in AHE measurements were obtained at saturation field (i.e., \( H_{\text{ext}} = H_{\text{sat}} \approx 600 \text{ mT} \)), 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 Figure 3a such account of external magnetic field influence results in very good agreement of oscillations behavior 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 \( H_{\text{ext}} = 0 \), the character of the oscillation damping returns to quadratic. This is well illustrated on Figure 3b, where calculations are presented in comparison with results of SHE studies at zero applied external magnetic field (filled circles).

Besides, in addition to SHE measurements, by knowing the value of detected spin-Hall current \((I_{\text{SH}} \approx 30 \mu A)\) and applied electrical current \((I_{\text{inj}} \approx 500 \mu A)\), it is possible to estimate the spin-polarization coefficient. Using equation \( I_{\text{SH}} = I_{\uparrow} - I_{\downarrow} = P \cdot I_{\text{inj}} \) [15], where \( I_{\uparrow} \) and \( I_{\downarrow} \) are the current with spin up and down, respectively, and \( P \) is the spin polarization in trilayer magnetic film structure, we obtain \( P \approx 0.06 \). Moreover, the specific feature of the investigated film system is that the value of spin polarization depends on peculiarities of IEC in these structures. Thus, estimated above value of \( P \) is maximal for investigated Fe/xAu/Tb structure and corresponds to certain thickness of Au spacer. Hence, changing nonmagnetic spacer (N) thickness in M/N/M film structure it is possible to change spin-polarization coefficient.

4. Conclusions

By means of new technique based on Spin-Hall effect it was shown that the behavior of interlayer exchange coupling oscillations in trilayer Fe/Au/Tb structures is possibly influenced by the external magnetic field. It was proposed 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. The presented technique also allows estimation of the spin-polarization coefficients of film structures.

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