

INTERLAYER EXCHANGE COUPLING, SPIN PUMPING AND SPIN TRANSPORT IN METALLIC MAGNETIC SINGLE AND BILAYER STRUCTURES

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Interlayer exchange coupling in thin films is one of the cornerstones of modern spintronics-based technology. This phenomena has been an active area of research for several decades. The focus of this paper is a few coupling mechanisms relevant in ulta-thin film structures. We review static interlayer exchange coupling, providing a brief overview of various coupling mechanism including a new mechanism of non-collinear coupling which is attractive to spintronics applications. The next part discusses proximity polarization coupling which can appear as a dominating coupling mechanisms in Stoner enhanced materials. The last part reviews spin-pumping as a form of dynamic coupling. A description of spin-pumping is presented as an extension of static, RKKY coupling into dynamic coupling by allowing for a time-delayed response. This approach makes a natural connection between static and dynamic coupling. We also present a detailed derivation of the conventional spin-pumping theory in a reparameterized form. This model is only applicable for highly conductive materials but fails for materials with large spin-orbit coupling. In view of this we review several spin-pumping studied in Au, Ag, Pd and Pt which explore the adequacy of this model and its limits.

The nature of the interlayer exchange coupling in FM/SL/FM (FMs are ferromagnetic layers, SL is spacer layer) dependents strongly on the electronic structure of the SL. The coupling across majority of metallic spacer layers oscillates between antiferromagnetic and ferromagnetic as a function of the spacer layer thickness. These oscillations originate from the sharp transition in momentum space between filled and unfilled states at the Fermi surface of the spacer layer [1]. The models show that the critical spanning vectors of the Fermi surface of the spacer layer determine the oscillation period [2].

Interlayer coupling has been observed across a majority of 3d, 4d and 5d non-magnetic metallic spacer layers [3–8]. For applications it is often desired to have FM/SL/FM structures with large antiferromagnetic coupling. The largest reported antiferromagnetic coupling (39 erg/cm^2) was observed in Co/Rh/Co multilayers deposited with molecular beam epitaxy (MBE) [9]. Unfortunately, the same structure deposited by magnetron sputtering, which is preferred deposition techniques for fabrication of devices, results in an order of magnitude smaller coupling strength. This reduction in coupling is attributed to inter-diffusion at the FM/SL interfaces in sputter deposited films [9].

Recently, it was demonstrated that a few atomic layers thick spacer layers can be used to control the angle between the magnetic moments of two ferromagnetic layers in FM/SL/FM [10,11]. The spacer consists of a nonmagnetic material (NM) alloyed with ferromagnetic materials. Changing the nonmagnetic to ferromagnetic concentration ratio in the spacer allows for

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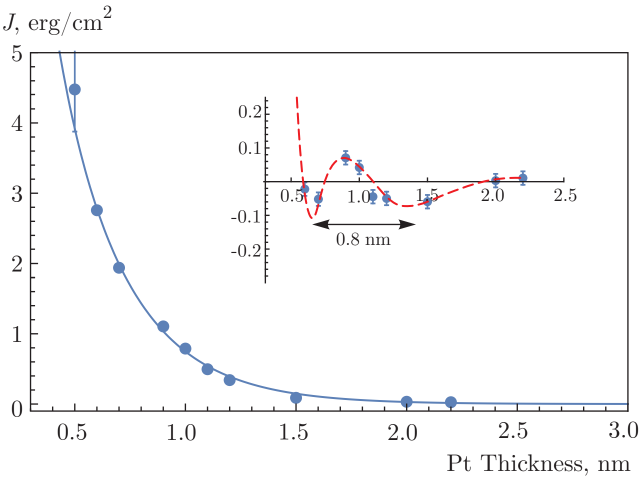

Fig. 1. Interlayer exchange coupling strength vs. thickness of Pt spacer layer. The line is a fit using an exponential fit derived from free energy of the Landau theory of phase transitions, yielding $\xi = 0.31 \pm 0.1$ nm. Inset shows the residuals to the fit, the dashed line is a guide for the eye. Reprinted with permission from Omelchenko Appl. Phys. Lett. **113**, 142401 (2018). Copyright 2018, American Institute of Physics

control of the relative angle between the magnetic moments of the ferromagnetic layers. The onset of the non-collinear alignment between the magnetic layers coincides with the advent of magnetic ordering in the spacer layer, which is induced by the surrounding ferromagnetic layers or is inherent to the spacer layer.

Coupling through polarizable spacer layers (Pt or Pd) is predominantly of ferromagnetic nature with exponentially decreasing strength by increasing the spacer layer thickness. An oscillatory coupling is superposed on top of the ferromagnetic coupling background, which does not affect the sign of the coupling [12]. The results of [13] and [14] indicate that the interlayer exchange coupling through Pt is dominated by proximity induced magnetization as oppose to RKKY like oscillatory coupling behavior observed for weakly polarized materials (Au, Cu, Ag). This is not surprising considering that Pt is a Stoner enhanced material and therefore is able to mediate long range magnetic order. The ferromagnetic proximity coupling decays exponentially with increasing Pt thickness on a length-scale of $\xi = 0.31$ nm, see Fig. 1. The coupling is representative of the induced magnetization inside of Pt. This length-scale is very similar to the length-scale of induced magnetic moment in Pt in the Co/Pt structures as studied by XMCD [15], $\xi_{XMCD} = 0.41$ nm.

So far the discussion is focused on time-independent coupling, however, the dynamics of the ferromagnet can also lead to coupling by spin-pumping. The concept of spin-pumping comes from a general ideas of reaching thermodynamic equilibrium in the presence of interface spin dependent scattering of NM electrons at the FM/NM interface. Quantitatively spin-pumping was first introduced by using formal spin algebra treatment of the spin dependent scattering of NM electrons at the FM/NM interface [16] leading to the generation of spin current acting as a peristaltic spin-pump. Alternatively, it was shown that the origin of spin-pumping arises from time retarded interlayer exchange coupling [17]. The advantage of the first treatment is that it introduces explicitly the spin-pumping parameters and allows one to extend this concept to the spin transport in NM by using spin diffusion theory. The second treatment shows that spin-pumping is just a direct extension of time retarded interlayer exchange coupling and allows one to extent this concept to systems with strong electron spin correlation effects.

A very clear example of dynamic coupling by spin-pumping through Au was presented in [18]. Performing angular dependent ferromagnetic resonance (FMR) on GaAs/16Fe/16Au/40Fe films the authors were able to study the line-width of the two magnetic layers, 16Fe and 40Fe. As the resonance fields of the magnetic layers cross, the spin-pumping contribution to line-width also drops, see Fig. 2. This is in perfect agreement with spin-pumping theory since at the crossing point the magnetic layers are compensating each others losses due to spin-pumping.

Usually spin-pumping manifests itself as an effect on the FMR line-width or the measured magnetic damping. However, it can also lead to a driving toque which can also generate precession. In [20] the authors used a temporal and spacial resolved magneto-optical Kerr effect to study the response of 12Fe due to driving of 16Fe in 16Fe/nAu/12Fe structures. It was found that the 12Fe response is out-of-phase with the 16Fe precession which a consequence of the fact that spin-pumping toque is proportional to the time-derivative of the magnetic moment and therefore is 180° out-of-phase with the source.

Spin-pumping into materials such as Au, Ag and Cu is in good agreement with the conventional spin-pumping model [19]. However for Stoner enhancement materials such as Pd and Pt, the interpretation of the spin-pumping model leads to an unusual limit. Magnetic damping studies on spin-pumping into Pd found that the spin relaxation time ($\tau_{sf}^{\mathrm{Pd}} = 1.70 \cdot 10^{-14}$ s) is quite similar to the electron momentum relaxation time ($\tau_{el}^{\mathrm{Pd}} = 1.91 \cdot 10^{-14}$ s). It can be shown that in this limit the spin-pumping model would suggest that Pd acts better then a perfect spin-sink (absorber of spin current).

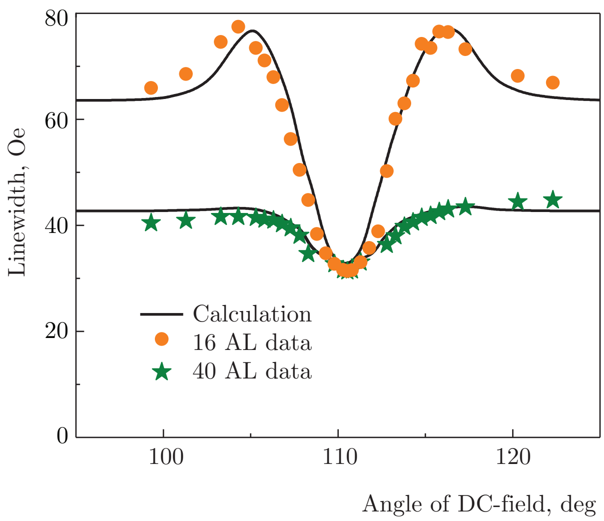

Fig. 2. Dependence of FMR linewidth in the 16Fe and 40Fe layers. Notice that the resonant field crossing the contribution of spin current is entirely removed [18]. The solid line is calculation using the spin net flow $\mathbf{I}_{sp}$(16Fe)–$\mathbf{I}_{sp}$(40Fe) for the 16Fe/Au interface and vice versa for the Au/40Fe interface. Spin current was calculated using conventional spin-pumping theory [19] with the magnetic parameters for 16Fe and 40Fe. Notice that the thinner layer exhibits an increase in the spin-pumping damping before it drops down to zero. This clearly shows that the phase of precession plays an important role. Close to the crossing of resonance fields it can even enhance the damping. The thicker layer just show a gradual drop to the bulk damping. AL — atomic layer

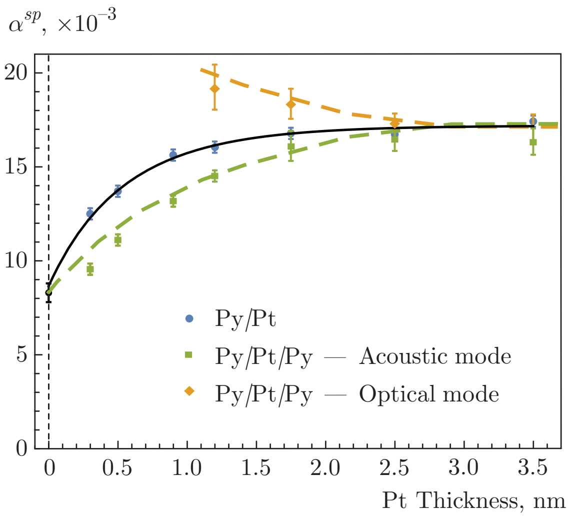

Fig. 3. Damping with increasing thickness of Pt for the Py/Pt(d_{Pt}), the acoustic mode of Py/Pt(d_{Pt})/Py and optical mode of Py/Pt(d_{Pt})/Py. The solid line is a fit to the Py/Pt(d_{Pt}) data using the conventional spin-pumping model. The dashed lines are simulations of the damping for the acoustic and optical modes by the process described in Omelchenko et al. [8]

For Pt the situation is even more unnatural since τ_{sf}^{Pt} is estimated to be $\sim$ 10 larger than τ_{el}^{Pt}. Pt therefore provides a good test for the conventional spin-pumping model. However, the difficulty of testing spin-pumping in Pt is that it mediates proximity induced coupling, see Fig. 1, on similar length-scales as the spin-pumping length scale. In [8] the effect of proximity coupling was utilized in FMR measurements to study the behaviour of spin-pumping through Pt. The proximity coupled structure resulted in two FMR modes, in-phase and out-of-phase precession of the two magnetic layers. The in-phase precession resulted in a suppression of spin-pumping induced damping, similar to the result of [18] for reduction of the line-width during mode crossing in 16Fe/16Au/40Fe structure. The out-of-phase precession led to enhancement of the magnetic damping. This is inline with the spin-pumping model since for out-of-phase precession the two magnetic layers are exchanging spin current of opposite polarization and effectively enhancing each others damping, see Fig. 3. It was found that all the data could be consistently analyzed with two spin-pumping parameters, spin diffusion length (δ_{sd} = 1.1 nm) and spin-mixing conductance ($\tilde{g}_{\uparrow\downarrow} = 4.3 \cdot 10^{15}$ cm^{-2}). This result emphasize the robustness of the spin-pumping/spin diffusion model.

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