Spin Pumping and Non-Uniform Magnetic Excitation in Spin-Torque FMR Studies of the Spin Hall Effect

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Primary CNF Tools Used: GCA 5x stepper, AJA sputtering tool

Abstract:

Spin-torque ferromagnetic resonance (ST-FMR) is a technique that was first used to show a surprisingly strong spin Hall effect (SHE) in certain heavy metals (HM) [1]. This method has since been widely deployed in the study of spin-orbit torques in HM/FM bilayers. However, recently it is unclear that ST-FMR always provides accurate, quantitative measures of the damping-like spin-torque efficiency ξ_{DL}, principally because of the unsettled role of spin-pumping and the inverse SHE in ST-FMR, but also because of the assumption that only the uniform mode is excited. Here we report on an extensive ST-FMR study of Pt/FM and HM/spacer/FM trilayers chosen such that the spin pumping effect is both strong and variable. We show that spin pumping, when significant, subtracts from the antidamping torque signal, resulting in $\xi_{FMR} < \xi_{DL}$. These results explain why ST-FMR often underestimates ξ_{DL} in comparison to quasi-static second harmonic results, the latter of which are generally confirmed by ST switching of MTJs.

Summary of Research:

Thin film samples were deposited onto 100 mm silicon wafers using our magnetron sputtering system. Structures were composed of, from bottom to top, Ta(1)/HM(t_{HM})/FM(t_{FM})/MgO(2)/Ta(1) with numbers in parenthesis representing the thickness of the layer in nanometers and t_{HM} and t_{FM} are the thicknesses of the heavy metal (HM) and ferromagnetic (FM) layers, respectively. Stacks were then patterned into 20 × 10 μm^2 micro-strips using photolithography with the 5X g-line stepper at CNF and etched using our own ion milling system. The contacts were made using the AJA sputtering system at CNF. The schematic of our devices and measurement is shown in Figure 1.

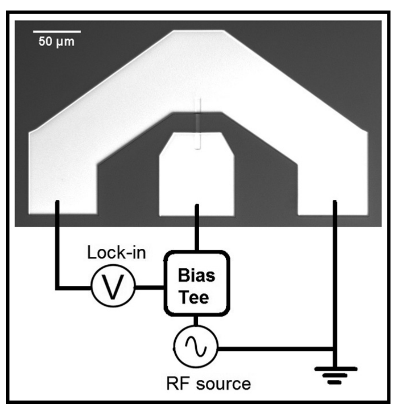

Figure 1: Microstrip with dimensions 20 × 10 μm^2 after fabrication and a schematic of the ST-FMR measurement.

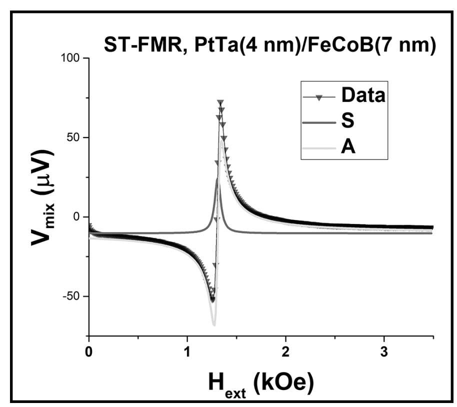

Figure 2: Example of voltage output from ST-FMR and a magnetic field sweep. The Lorentzian is fit with symmetric and antisymmetric components shown.

The spin torque efficiency (ξ) in these samples was determined using spin-torque ferromagnetic resonance (ST-FMR) [1,2]. A microwave frequency (RF) current is driven through the microstrip, which induces magnetic precession in the ferromagnetic layer via spin transfer torque. A magnetic field is swept at 45° to the microstrip and the voltage is measured by a lock-in amplifier. A lineshape analysis is done by fitting a Lorentzian function with symmetric (S) and antisymmetric (A) components as shown in Figure 2. The ratio of the prefactors S and A yield ξ_{FMR}.

Traditionally, spin pumping is not taken into account, and without the presence field-like torque ξ_{FMR} would be the same as the damping-like torque efficiency ξ_{DL}. Experimentally we achieve samples without a strong field-like torque by insertion of a Hf spacer layer between the HM and FM layers in the case of Pt based samples such as $Pt_{0.9}Ta_{0.1}$ [2]. However, when spin pumping is accounted for, the expression for ξ_{FMR} becomes more complicated as shown by the equation in Figure 3. Here we have separated two terms for the damping-like spin torque efficiency: one for the value obtained from the traditional analysis of the FMR signal, and one for the value obtained from the portion of the signal due to spin pumping. The entire portion of the signal subtracted from the FMR ξ_{DL} is due to spin pumping. Importantly, we can see some terms that would cause this signal to become larger such as higher HM resistivity samples and samples with thicker HM and FM layers.

We expected that the $Pt_{0.9}Ta_{0.1}$ alloy is a good HM for showing spin pumping because of its higher resistivity and large spin torque efficiencies as a Pt system. The result of an ST-FMR measurement of an 8 nm $Pt_{0.9}Ta_{0.1}$ sample with varying FeCoB thickness is shown in Figure 4. Here we see that the signal inferred from traditional FMR analysis is ξ_{DL} = 0.064. However, it is clear that ξ_{FMR} changes as a function of FM thickness. This is due to spin pumping and has the predicted behavior of subtracting from the signal and increasing in magnitude as the FM layer becomes thicker, as predicted in Figure 3. A quantitative analysis yields ξ_{DL} = 0.34 as measured from the spin pumping signal. This is much larger than the signal from traditional ST-FMR and agrees more closely with values obtained from similar Pt-based alloy systems [4] and with our own second harmonic measurements of $Pt_{0.9}Ta_{0.1}$ of around ξ_{DL} = 0.3 as well. Using different thicknesses of $Pt_{0.9}Ta_{0.1}$ we also observed spin pumping effects that were in relative strength to the thickness of the HM layer.

$$\xi_{\mathrm{FMR}} = \xi_{\mathrm{DL}}^{\mathrm{FMR}} - \frac{\boldsymbol{\xi}_{\mathbf{DL}}^{\mathbf{SP}}\, e^{-\frac{t}{\lambda_{\mathrm{Hf}}}}}{\rho_{\mathrm{N}}} \frac{A}{(\Delta\rho/\rho)_{\mathrm{SMR}}} \left(B t_{\mathrm{F}} \mathrm{t}_{\mathrm{N}} + \frac{{\xi_{\mathrm{DL}}^{\mathrm{FMR}}}^2}{B t_{\mathrm{F}} t_{\mathrm{N}}} \right)$$

$$A = \frac{h}{e} \frac{\gamma \mu_0}{32\pi} \tanh\left(\frac{t_N}{2\lambda_N}\right) \frac{\sigma_{\mathrm{F}} t_{\mathrm{F}}}{\sigma_{\mathrm{N}} \mathrm{t}_{\mathrm{N}} + \sigma_{\mathrm{F}} t_{\mathrm{F}}} \frac{1}{\alpha} \frac{\sqrt{H_{\mathrm{R}}(H_{\mathrm{R}} + 4\pi M_{\mathrm{eff}})}}{(H_{\mathrm{R}} + 2\pi M_{\mathrm{eff}})} \qquad B = \frac{\mu_0 e M_s}{\hbar} \sqrt{1 + \frac{4\pi M_{\mathrm{eff}}}{H_{\mathrm{R}}}}$$

Figure 3: The equation used for ST-FMR analysis with a spin pumping model.

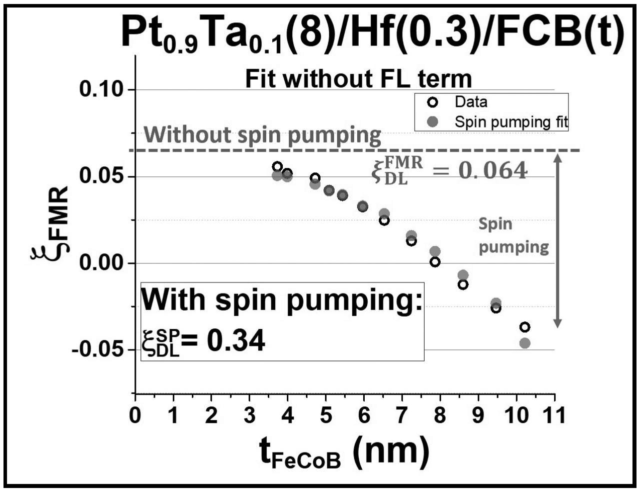

Figure 4: ST-FMR signal from an 8 nm $Pt_{0.9}Ta_{0.1}$ sample with Hf spacer and FeCoB. Fits to the data without the spin pumping model and with the spin pumping model are both shown.

Quantitative analysis yields results that agree well with other measurements, unlike the original analysis methods used which underestimate ξ_{DL}. We plan to do more experiments with different HM layers and also to fabricate more samples where we manipulate parameters such as the resistivity and also the spin torque signal itself with varying spacer layers. We expect to be able to model those results as well as those that also include a field-like torque term.

Conclusions and Future Steps:

We show that the spin pumping signal affects ST-FMR by subtracting from the signal and thus causing an underestimation of the damping-like spin torque efficiency of the HM layer if using only traditional analysis. In the $Pt_{0.9}Ta_{0.1}$ system, there is a clear suppression of the signal and it behaves in accordance with the equation in Figure 3.

References:

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[3] Yongxi Ou, et al. Phys. Rev. B 94, 140414 (2016).

[4] L. Zhu, D.C. Ralph, and R.A. Buhrman, Phys. Rev. Applied 10, 031001 (2018).