LARGE SPIN HALL CONDUCTIVITY IN PT AND Ni$_x$Cu$_{1-x}$ AS MEASURED WITH NON-CONTACT MICROWAVE SPECTROSCOPY

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By use of microwave spectroscopy, we have measured the spin Hall effect (SHE) and spin transparency in bilayers of Ni$_{80}$Fe$_{20}$/Pt. The method uses a phase-sensitive amplitude analysis of FMR spectra with unpatterned thin films that are proximate to, but not electrically connected with, a coplanar waveguide [1]. Both SHE and iSHE are measured simultaneously, as mandated by Onsager reciprocity. The method does not require the samples to have an easy axis, nor knowledge of the precession angle. Damping is simultaneously measured, permitting self-consistent fitting of the SHE and spin pumping signals [2]. In agreement with previous reports [3], the spin transport efficiency between Ni$_{80}$Fe$_{20}$ and Pt is $<< 1$, presumably due to interfacial spin memory loss. Also, the transparency is a strong function of deposition order, with a 3x reduction when Ni$_{80}$Fe$_{20}$ is grown on Pt. While the effective SHE signal and spin diffusion length are comparable to previous reports [4], substantial spin memory loss implies a larger value for the intrinsic SHE ratio of Pt ($\sim$ 0.4) than previously reported.

We also report a large spin Hall conductivity, $\sigma_{SH}$, in high resistivity, paramagnetic Ni$_{60}$Cu$_{40}$ [5]. The value is comparable to what we reported for Pt [2]. Again, broadband FMR measurements of ferromagnet/nonmagnet bilayers provide an accurate measure of $\sigma_{SH}$, and simultaneously the contribution of spin pumping to damping, when the various contributions to the inductively detected signal are analyzed as described in [1]. In a series of samples with the layer structure substrate/Ta(3)/Py(3.5)/Ni$_x$Cu$_{1-x}$(d)/Ta(3) (thickness in nm), we varied Ni fraction $x$ for $d = 10$ nm and varied thickness $d$ for $x = 0.6$, a composition with a magnetic ordering critical temperature $T_C = 140$ K. FMR measurements at room temperature showed a substantial $\sigma_{SH}$ for all compositions we deposited, $0.3 \leq x \leq 0.75$, with a maximum at $x = 0.7$ where $T_C = 270$ K. For the thickness series at $x = 0.6$, we use the approach detailed in [2] to extract a spin diffusion length of $(8.3 \pm 0.4)$ nm and a spin Hall ratio of $1.05 \pm 0.18$. Both values are about twice as large as we reported for Pt [2].