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Phase-Sensitive Detection Of The AC Inverse Spin Hall Effect

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Spin pumping [1] is a significant source of damping in ultrathin ferromagnet/normal metal bilayers. In these structures, the magnetization relaxation is enhanced via the diffusion of spin currents across the bilayer interface. The pumped spin currents have both a small dc and dominant ac contributions. The nonlinear dc spin current contribution that arises in ferromagnetic resonance (FMR) has been extensively studied in electrical dc measurements that are enabled by means of the inverse spin Hall effect (iSHE) in the normal metal [2]. The ac charge voltage generated in FMR due to the ac iSHE should be linear in the magnetization precession and thus much larger than the corresponding dc voltage for small precession cone angles [3]. However, any measurement of the ac iSHE voltage needs to take the linear inductive voltages due to Faraday's law into account, as magnetization dynamics in ferromagnet/normal metal bilayers result in both, inductive and possible ac iSHE voltages. These voltage signals are always superimposed and cannot be separated in a measurement scheme that is only sensitive to the magnitude of the signal [4-7]. Moreover, inductive and ac iSHE voltages are estimated to be of the same order of magnitude for typical nm-thick ferromagnetic layers in contact with Pt and share identical symmetry with respect to magnetization orientation. The only qualitative difference between inductive and ac iSHE voltages is their expected phase difference of $\pi/2$. We thus use a phase-sensitive, quantitative technique to separate inductive and ac iSHE signals in a variety of $Ni_{81}Fe_{19}$/normal metal thin film bilayers at room temperature. All samples show the expected behavior in terms of damping and dc iSHE voltages from which we find a dc spin Hall angle Θ_{SH}=0.1 for Pt [8]. Our ac iSHE experiments [9] are carried out using $Ni_{81}Fe_{19}$/normal metal bilayers deposited simultaneously with the dc structures. Using Ta, W, Pd, Cu or Nb as the normal metal, we find that the inductive contribution dominates over any ac iSHE signal, in agreement with simple estimates based on the extracted dc spin Hall angles for these materials. However, for Pt, we find a surprisingly large ac iSHE contribution that has a significantly different phase than expected. Similar results are also found in $Ni_{81}Fe_{19}$/Cu/Pt trilayers, excluding the possibility of an interfacial origin of the large ac iSHE signal. Modeling of our experimental results in the context of the ac iSHE requires a complex-valued spin Hall angle Θ_{SH} of Pt with $\Theta_{SH} \approx 1$ and $\arg(\Theta_{SH}) \approx 110°$ in the investigated frequency range of 7 to 20 GHz.

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