MAR11-2010-000310

Abstract for an Invited Paper
for the MAR11 Meeting of
the American Physical Society

Quantifying Spin Hall Effects in Nonmagnetic Metals[1]

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Spin Hall effects intermix spin and charge currents even in nonmagnetic materials and, therefore, offer the possibility to generate and detect spin currents without the need for using ferromagnetic materials. In order to gain insight into the underlying physical mechanism and to identify technologically relevant materials, it is important to quantify the spin Hall angle γ, which is a direct measure of the charge-to-spin (and vice versa) conversion efficiency. Towards this end we utilized non-local transport measurements with double Hall bars fabricated from gold and copper.[3] In principle, this geometry permits the study of spin currents both generated and detected via spin Hall effects. We observe an unusual non-local resistivity that changes sign as a function of temperature. However, this results is quantitatively similar in gold and cooper, indicating that the non-local signals are not due to spin transport. An analysis of the data based on a combination of diffusive and quasi-ballistic transport leads to an upper limit of $\gamma < 0.027$ for gold at room temperature. Therefore we developed an approach based on spin pumping, which enables us to quantify even small spin Hall angles with high accuracy. Spin pumping utilizes microwave excitation of a ferromagnetic layer adjacent to a normal metal to generate over a macroscopic area a homogeneous *dc* spin current, which can be quantified from the line-width of the ferromagnetic resonance. In this geometry voltages from spin Hall effects scale with the device dimension and therefore good signal-to-noise can be obtained even for materials with small spin Hall angles. We integrated ferromagnet/normal metal bilayers into a co-planar waveguide and determined the spin Hall angle for a variety of non-magnetic materials (Pt, Pd, Au, and Mo) at room temperature. Of these materials Pt shows the largest spin Hall angle with $\gamma = 0.013 \pm 0.002$.[4]

[1]Financial support was through U.S. Department of Energy, Office of Science under Contract no. DE-AC02-06CH11357.
[2]It is a great pleasure to acknowledge my excellent collaborators: O. Mosendz, G. Mihajlović, V. Vlaminck, H. Schultheiß, J. E. Pearson, F. Y. Fradin, S. D. Bader, M. A. Garcia, T. Hirahara, and G. E. W. Bauer.
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