Inverse spin Hall effect measurements in patterned $Ni_{80}Fe_{20}$/normal metal bilayers*

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Recent activity in spin transport research has included a focus on spin Hall effects, which arise from spin-orbit interactions, rather than exchange or spin-lattice effects. Spin orbit coupling in normal metals (NM) leads to a conversion of pure spin current into a charge current, which is perpendicular to both the spin current direction and the spin polarization. This is known as the inverse spin Hall effect and it generates a voltage across a spin-current-carrying sample. The strength of the inverse spin Hall effect is characterized by a single dimensionless parameter, the spin Hall angle, which is materials-specific. We studied the inverse spin Hall effect in $Ni_{80}Fe_{20}$/NM bilayer structures by generating pure spin currents inside the NM layer through spin pumping at the $Ni_{80}Fe_{20}$/NM interface. Integrating a patterned $Ni_{80}Fe_{20}$/NM bilayer into a coplanar waveguide transmission line enables us to excite large angle magnetization precession in $Ni_{80}Fe_{20}$ via *rf* excitation, which in turn generates a *dc* spin current in the adjacent NM. Ferromagnetic resonance (FMR) in $Ni_{80}Fe_{20}$ and the *dc* voltage across the $Ni_{80}Fe_{20}$/NM were measured simultaneously as a function of the applied magnetic field. A strong *dc* signal across the $Ni_{80}Fe_{20}$/NM is observed at the FMR position, and its magnitude is dependent on the power of the *rf* excitation and the angle of the applied magnetic field. We identified two distinct contributions to the *dc* voltage: one symmetric with respect to the FMR resonance position, and the other antisymmetric. Our analysis shows that the antisymmetric contribution is due to an anisotropic magnetoresistance effect (AMR) in the $Ni_{80}Fe_{20}$ layer and is present even in single-layer $Ni_{80}Fe_{20}$ films. The second, symmetric, contribution to the measured *dc* voltage is attributed to the inverse spin Hall effect. The sign and strength of the symmetric contribution is dependent on the NM used in the experiment; we uniquely determine in quantitative fashion compared to other studies, the spin Hall angle for Pt, Au and Mo by fitting the experimental data to a self-consistent theory, which accounts for both the AMR and inverse spin Hall effect contributions. This study provides insight for identifying materials that are useful for spintronic applications.

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