MAR11-2010-003041

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

Spin Hall Effects in Ferromagnet-Semiconductor Heterostructures

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The effect of spin-orbit coupling on charge transport has long been studied in the form of the anomalous Hall effect in ferromagnets. Charge current in a ferromagnetic channel is intrinsically spin polarized, and asymmetric transverse scattering of spin-up and spin-down electrons due to spin-orbit coupling leads to charge accumulation on the channel edges. Recent breakthroughs in the ability to inject and detect non-equilibrium spin populations in non-ferromagnetic materials have opened up new avenues to study related phenomena. Of particular interest is the spin Hall effect (SHE) in which an ordinary charge current induces a transverse spin current. The resultant spin accumulation at the channel edges was first detected optically [Y. K. Kato *et al.*, Science 306, 1910 (2004) ; J. Wunderlich *et al.*, Phys. Rev. Lett. 94, 047204 (2005)]. We report on an all-electrical measurement of the SHE in Fe/n-$In_xGa_{1-x}As$ heterostructures. The edge spin accumulation is detected with spin-sensitive Fe/Schottky tunnel barrier contacts. We investigate the bias and temperature dependence of the SHE and successfully determine the skew and side-jump contributions [E. S. Garlid *et al.*, Phys. Rev. Lett. 105, 156602 (2010)]. Additionally, we have studied the inverse spin Hall effect (iSHE), in Fe/n-GaAs devices. Spin current injected into n-GaAs by a biased Fe/Schottky contact results in a spin-dependent Hall voltage. The iSHE signal is an order of magnitude larger than that expected from SHE measurements in the same heterostructure. Temperature dependence, nuclear magnetic resonance, and field cycling measurements show conclusively that the iSHE is coupled to the dynamically polarized nuclear spins. We have therefore discovered a new contribution to spin Hall effects: the hyperfine coupling. Work done in collaboration with E.S. Garlid, Q.O. Hu, C.J. Palmstrøm, and P.A. Crowell. Funding provided by NSF DMR 0804244, ONR MURI, and NSF MRSEC and NNIN programs.