

# Spin and orbit torques in artificial alloy thin films and heterostructures

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Spin and orbital torques have become crucial for fast and energy efficient magnetization switching in spintronic devices, such as spin-orbit torque (SOT) magneto-resistive random access memories (MRAMs). When a longitudinal charge current passed through a nonmagnetic thin film, spin and orbital currents arise along the transverse direction due to the spin Hall effect (SHE) and orbital Hall effect (OHE), respectively, and can exert torques on the adjacent ferromagnetic layer, as schematically illustrated in Fig.1. Large spin and orbital torque efficiencies are essential for the development of SOT-MRAMs and related technologies. Materials such as topological insulators and heavy metals exhibit significant spin Hall efficiencies due to their large spin orbit coupling, while light metals are reported to possess strong orbital Hall effects. In this talk, we will present enhanced spin and orbital torque efficiencies in well-engineered artificial heterostructures and alloy thin films, including topological insulator BiSb/Ti/NiFe heterostructures [1] and nonequilibrium RuMo alloy thin films [2].

All the thin films were deposited on sapphire *c*-plane substrates using an ultra-high vacuum magnetron sputtering system. The structural characteristics of these films were analyzed using reflection high energy electron diffraction, X-ray diffraction, atomic force microscopy, and high-angle annular dark-field scanning transmission electron microscopy. Coplanar waveguide devices were fabricated using conventional UV lithography to assess spin and orbital torque efficiencies via spin-torque ferromagnetic resonance techniques.

We investigated the effect of the Ti insertion layer on the torque efficiency of two series of samples, BiSb/NiFe and BiSb/Ti/NiFe, under as-deposited, room-temperature aging and annealing conditions. Samples with the Ti layer showed a multifold increase in torque efficiency compared to those without Ti insertion. Atomic resolution microstructural analysis clearly illustrates the interfacial chemistry where Ti effectively prevents the interdiffusion of Ni and Sb. This interfacial chemistry near Ti at the interface of BiSb/NiFe significantly enhances torque efficiency. On the other hand, epitaxial thin films of a fully nonequilibrium hcp-Ru<sub>50</sub>Mo<sub>50</sub>(0001) were prepared as a chemically disordered alloy with an expected negligible intrinsic SHE. Structural analysis confirmed epitaxial growth and atomic-scale alloying of the thin films. Unlike the modest torque efficiency (~0.4%) observed for Ru<sub>50</sub>Mo<sub>50</sub>/CoFeB, the torque efficiency for the Ru<sub>50</sub>Mo<sub>50</sub>/Ni bilayers reached approximately 30% with a long-range relaxation length. The observed large variation in torque efficiency with the ferromagnetic layer could be attributed to the OHE. Interestingly, a small torque efficiency was observed for Ru/Ni, indicating that the nonequilibrium Ru<sub>50</sub>Mo<sub>50</sub> composition enhances the OHE. Furthermore, inserting a Ru layer between the Ru<sub>50</sub>Mo<sub>50</sub> and Ni layers maintains and improves torque efficiency, indicating orbital transport through Ru. These results not only show the significance of artificially engineered heterostructures and nanoalloy thin films for potential applications in spin and orbital torque technologies, but also contribute to the understanding of the intricate relationships between nanostructures and spin-orbitronics.

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## References

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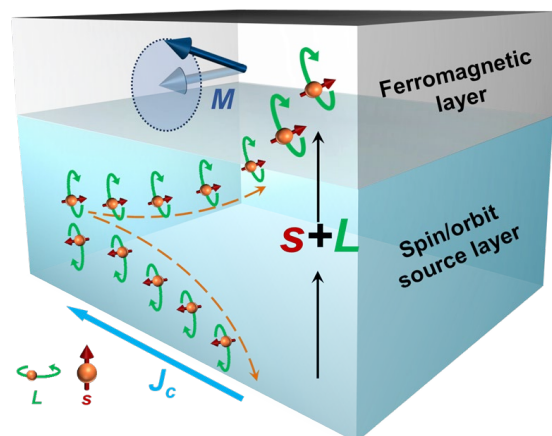


Fig. 1. Illustration of the spin and orbital Hall effects and interaction with the magnetic moment of the adjacent ferromagnetic layer.