Abstract

Low-dimensional quantum materials provide an excellent platform for studying a wide range of field-driven linear and nonlinear transport phenomena in the presence of spin-orbit coupling (SOC). Additionally, the geometric properties of electronic bands can strongly modify transport behavior in these systems and give rise to a plethora of anomalous linear and nonlinear responses. This thesis addresses various transport phenomena involving spin-orbit coupling and geometric properties of the electronic wavefunction. Specifically, we investigate electrically induced spin polarization and nonlinear Hall effects in nonmagnetic, time-reversal symmetric systems, with a particular focus on how crystal symmetry, momentum-dependent SOC, and band topology govern these transport phenomena.

In the first part, we study the current-induced spin polarization in noncentrosymmetric materials, where Rashba SOC gives rise to the Edelstein effect. We demonstrate that the nature of the induced spin polarization is strongly governed by the underlying point-group symmetries of the system, specifically C_n and C_{nv}. These symmetries restrict the allowed forms of SOC Hamiltonians, permitting both linear and higher-order (cubic-in-k) Rashba and Dresselhaus terms. We show that surfaces with C_n symmetry can host both orthogonal and non-orthogonal spin polarizations relative to an applied electric field. In contrast, systems with C_{nv} symmetry exhibit exclusively transverse spin polarization, independent of higher-order SOC contributions. Furthermore, we uncover qualitatively distinct energy-dependent spin-polarization behavior arising from cubic-in-k SOC compared to linear SOC, which can be tuned, for example, via chemical doping.

Interestingly, the Rashba–Dresselhaus system under C_n symmetry exhibits a symmetry-protected persistent spin texture (PST) at equal SOC strengths, resulting in the suppression of field-induced spin polarization. In the second part, we therefore study the non-linear Hall response in this system. Exactly at the PST point, we find that both the linear and nonlinear Hall responses vanish. However, a small deviation from the PST regime leads to a pronounced enhancement of the nonlinear Hall response. This behavior originates from the evolution of the electronic structure, which develops a nearly degenerate band structure with a single node for the near PST point and strongly modifies geometric quantities such as the Berry curvature, Berry curvature dipole, and Berry connection polarizability. This interplay between nodal band geometry and the nonlinear Hall response extends beyond Rashba–Dresselhaus systems to a broader class of materials with tunable band crossings.

In the last part, we explore nonlinear Hall transport in tunable two-dimensional Dirac semimetals that preserve time-reversal symmetry and can host single-node, double-node, or nodal-ring band structures depending on model parameters. We analyze second and third-order Hall responses driven by the quantum geometry of the electronic wavefunction. The second-order Hall effect, governed by the Berry curvature dipole, is found to be strongly enhanced in the inversion symmetry broken single-node phase, while it vanishes in the nodal-ring phase where inversion symmetry is retained. In contrast, the third-order Hall response, arising from the Berry connection polarizability, is maximized in the nodal-ring phase, particularly when the Fermi energy is tuned close to the band edge. This contrasting behavior is attributed to the distinct momentum-space distributions of the underlying quantum-geometric quantities.

In summary, this thesis establishes crystal symmetry and band topology as central principles for understanding and controlling electrically driven spin polarization and higher-order transport phenomena in low-dimensional quantum materials, offering new routes for designing spintronic and nonlinear electronic properties.