論文の内容の要旨

Spin Hall Effect in Ferromagnets

(強磁性体におけるスピンホール効果)

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The spin Hall effect (SHE) is the fundamental charge-to-spin conversion mechanism in spintronics, which has been extensively studied in paramagnetic materials. Recent experimental results confirmed the existence of SHE in the ferromagnets but also caused a debate on whether the SHE would be affected by the ferromagnetic ordering. Hence, the crucial issues on SHE in ferromagnets are two-fold: i, its relationship with the anomalous Hall effect (AHE), which is widely considered to share the same mechanisms; ii, whether the SHE depends on the direction of magnetization.

In this dissertation, both numerical and analytical *ab initio* techniques are adapted to study the intrinsic SHE in various types of ferromagnets, in which I primarily focus on the above two issues. Through first principles calculations, relationship between the AHE and SHE are investigated, where I emphasize the unique features of anti-crossings of Bloch states with opposite spin. In such anti-crossings, due to the considerable difference between matrix elements in velocity and spin velocity operators, the Berry curvature and spin Berry curvature behave divergently, which results in the reduction of symmetry of spin Berry curvature comparing with the Berry curvature. The ubiquity of these anti-crossing implies that the intrinsic AHE and SHE may not have strong correlation, as evidenced in experiments. Subsequently, I find the intrinsic SHC in cubic phase ferromagnets (bcc-Fe and fcc-Ni) are highly anisotropic with respect to the direction of magnetization, *i.e.*, the change in the magnitude of intrinsic SHC for bcc-Fe is four-fold. The anisotropy of intrinsic SHC is closely related to the anti-crossings with opposite spin, where the interband matrix elements are enhanced when magnetization is rotated away from the quantization axis. To investigate the anisotropic SHE in the ferromagnets, I choose two types of model Hamiltonian for analytical *ab initio* calculations: 2DEG with exchange interaction and Dirac ferromagnet. The intrinsic SHC is strongly anisotropic in both cases. In the 2DEG model, the anisotropy is attributed to the interplay of Rashba and Dresselhaus SOC and exchange interaction. In the Dirac ferromagnet, the anisotropy is attributed to the axial anisotropy induced by ferromagnetic ordering. Hence, the anisotropy of SHC does not disappear when the strength of magnetization is asymptotically approaching zero. It suggests that for intrinsic SHC in massive Dirac electron system, a non-trivial transition exists from a ferromagnetic state to paramagnetic state.