論文の内容の要旨

Current-spin conversion in Dirac semimetal thin film heterostructures
(ディラック半金属薄膜ヘテロ構造における電流-スピン流変換)

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Current-induced spin-transfer torque (STT) is an effective method to control the magnetization of ferromagnetic metal (FM) thin films by the current, paving the way for designing spintronic devices with low power consumption, fast speed, and high density. Recently, a new type of current-induced torque has been observed in heavy metal (HM)/FM and topological insulator (TI)/FM thin film heterostructures. The torque, known as spin-orbit torque (SOT), is of particular interest owing to the high effciency in manipulating the magnetization of FM layers. The SOT is attributed to current-induced spin accumulations at the interface of HM/FM and TI/FM heterostructures, which originates from the spin Hall effect (SHE) and/or the Rashba-Edelstein effect (REE). Therefore, identifying materials with considerable current-spin conversion effciency and clarifying their origin are critical to developing our understanding on these materials and realizing effcient current-induced SOT for application.

In this thesis, I present current-spin conversion in Bi-based material thin films by characterizing the current-induced SOT using Bi-based material/FM thin film heterostructures. An alternating ultrathin layer deposition (AULD) method is proposed to grow Bi-based alloy with controllable concentration. First, I demonstrate appreciable current-spin conversion effciency, exceeding an unity, in polycrystalline $Bi_{1-x}Sb_x$ alloy thin films. The $Bi_{1-x}Sb_x$ thickness, composition, and facet orientation dependences of the spin Hall conductivity (SHC) of the alloy indicate large current-spin conversion is primarily due to the intrinsic SHE in $Bi_{1-x}Sb_x$. The topological surface state of $Bi_{1-x}Sb_x$, if present, plays little role in current-spin conversion. Strikingly, the SHC of $Bi_{1-x}Sb_x$ increases markedly with temperature, following the temperature dependence of carrier density. Based on an analysis of spin current mobility, we suggest the thermally-excited massive Dirac electrons at the *L*-valley significantly contribute to this enhancement.

Second, I show the investigation on current-induced SOT in carrier-doped Bi/CoFeB thin film heterostructures to highlight the importance of massive Dirac carriers, including electrons and holes, to current-spin conversion. The Fermi level positioning is tunable by substituting Bi with Te and Sn. The current-spin conversion effciency of pristine Bi is found to reach ~ 2.7, which is the largest spin Hall angle detected so far. It is found that the SHC of Bi exhibits a plateau when the Fermi level is close to the Dirac point. Subsequently, the value drops dramatically with increasing electron and hole doping induced by Te and Sn substitution. The SHC of Bi is also demonstrated to be robust against the change of Bi thin film crystallographic orientation and resistivity. These results indicate the current-spin conversion of Bi, dominated by the intrinsic SHE, is correlated with the Fermi level positioning.

Third, I introduce the study on the structure, magnetic anisotropy and current-spin conversion in $Pt_{1-x}Bi_x$/Co/MgO trilayer systems. Bi atoms behave as impurities in the Pt host and the magnetic easy axis of an ultrathin Co layer in the trilayer points out-of-plane when the doping level x is smaller than ~ 0.5. $Pt_{1-x}Bi_x$ thin film converts to a Pt-$PtBi_2$ mixture for x beyond ~ 0.6. In this regime, the easy axis of the ultrathin Co layer changes from out-of-plane to in-plane. The resistivity of Pt-rich $Pt_{1-x}Bi_x$ increases with doping, whereas the SHC is hardly influenced by x. These results suggest Bi doping is an effective strategy to enhance the current-spin conversion effciency of Pt.

These studies provide the first experimental evidence that Dirac-like electronic band structure, which contains non-zero Berry curvature, is strongly correlated to the SHE. The findings advance understanding on the current-spin conversion process on Dirac materials and open pathways to develop material systems that allow generation of significant spin current.