学位論文の要約

題目　Spin-orbit Phenomena in Non-centrosymmetric Magnetic Multilayers
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序論

In the current tide of the explosive enhancement of data storage density, spin current is emerged as one of the most efficient ways to control the magnetization. Recently, the two methods of generating spin current using spin orbit coupling have been discovered. One way is the spin Hall effect which converts the charge current to the spin current inside the heavy metal layer. The other way is using the interfacial spin orbit coupling (*i.e.*, Rashba effect) which essentially requires the inversion symmetry breaking. The generated spin current transfers the angular momentum to the adjacent ferromagnetic layer, and the resulting torque so-called spin orbit torque (SOT) is eventually possible to switching the magnetization. Therefore, the charge-to-spin conversion efficiency is considered as a crucial factor for manipulating the magnetization. In this regards, investigating spin-orbit torque in various system possessing either spin Hall effect or inversion symmetry breaking gives the insight about the energy-efficient method of magnetization manipulation.

In this thesis, the spin-orbit phenomena, mainly about SOT in various magnetic multilayers and non-centrosymmetric superlattices are investigated. The spin torque generated by the charge-to-spin conversion can be quantified by means of AC harmonic voltage measurement. In the first part, spin current is generated by the spin Hall effect in the heavy metal, exerting the torque to the upper ferrimagnetic layer. The change of spin-orbit effective field with the temperature is consistent with the expectation from the conventional spin torque theory. Secondly, the SOT in non-centrosymmetric artificial superlattices which consist of three different elements is investigated. It is found that the enhancement of SOT in the superlattice is closely related to the crystalline structure accompanied with the electronic structure at the interface. The non-centrosymmetric multilayers not only suggest the way to control the magnetization in an efficient way, but also it could pave the way to find undiscovered spin orbit related phenomena.

１．Temperature dependence of spin-orbit effective fields in Pt/GdFeCo bilayers (Pt/GdFeCo 二層膜におけるスピン―軌道有効磁場の温度依存性)

Ultrafast dynamics and small net magnetic moment are two of the virtues in antiferromagnetically ordered materials. Recent vigorous studies on antiferromagnets as well as ferrimagnets have been inferring that those materials can be a next generation of the spintronic materials. However, many of the spintronic functionalities, such as spin torque manipulation of the magnetic moments, in those materials have yet to be fully demonstrated. In particular, how the spin orbit effective field acts on these is still in question and is of great interest. In this work, the temperature dependent spin orbit effective fields in the heavy metal (Pt)/ferrimagnet (GdFeCo) bilayer structure are quantified by the AC harmonic voltage measurement. GdFeCo is a ferrimagnetic material whose net magnetic moments are tunable by temperature. It is possible to realize an antiferromagnetic state (with no net magnetic moments) at so-called compensation temperature (T_M). The temperature dependence of the spin orbit effective field across the T_M in ferrimagnets is investigated.

Multilayers of SiN(5 nm)/Pt(5 nm)/$Gd_{25}Fe_{65.6}Co_{9.4}$(10 nm)/SiN(5 nm) were deposited on Si substrate by the magnetron sputtering. Then, the films were patterned into a microstrip line with a Hall bar structure, by photolithography and subsequently Ar ion milling. In order to understand the magnetic compensation temperature (T_M), DC measurements of anomalous Hall were carried out with varying the temperature. The square hysteresis loops indicate that the film maintains a perpendicular magnetic anisotropy in all the temperature range even after the device fabrication. The hysteresis loop is reversed at T ~120K, indicating the magnetization compensation temperature (T_M) is around 120 K. The AC harmonic voltage measurements were performed under applied current with different amplitudes at 337 Hz. Both the first and the second harmonic voltages were detected simultaneously by two lock-in amplifiers. The damping-like and field-like effective fields were calculated to understand their temperature dependent behavior. Temperature dependence of the damping-like effective field per charge current ($\Delta H_{DL}/J_e$) across T_M is analyzed. It turns out that the field-like effective field is an order of magnitude smaller than the damping-like effective field in all the temperature range. A rapid increase of $\Delta H_{DL}/J_e$ around T_M is observed. In the framework of the conventional spin torque theory, $\Delta H_{DL}/J_e$ should be inversely proportional to the net magnetization of GdFeCo. The results therefore could suggest that the reduction of the net magnetization of GdFeCo is the main factor of the $\Delta H_{DL}/J_e$ increase. It turns out that the damping-like torque efficiency (ξ_{DL} = 0.014 ± 0.002) simply scales with the total magnetization and is constant at all experimental temperature range.

２. Charge-to-spin conversion in the non-centrosymmetric artificial superlattice (中心対称性のない人工格子における電流スピン変換)

Increasing demands for information processing have expedited the development of faster and more energy-efficient magnetic data storage systems with high capacity. Magnetization switching has been intensively studied for energy-efficient writing schemes. In this scheme, altering magnetization between the up and down states is directly related to the energy consumption required to store information. Recently, magnetization switching by so-called spin–orbit torque (SOT) due to the angular momentum transfer of spin current converted from the charge current via spin Hall or Rashba effects has been demonstrated. Therefore, a system that can convert a charge current to a spin current more efficiently, that is, a system with a large effective spin Hall angle would be a much more energy-efficient system. In this study, we demonstrated the large SOT in inversion asymmetric artificial superlattices. In this superlattices, two different crystal structures [face-centered cubic Pt and A15 structured β-W(210)] composed of few atomic monolayers are in contact with 6 Å FCC Co layers, giving rise to a fully broken inversion symmetry for the whole structure.

Superlattices of Ta(1.5 nm)/[Pt(1 nm)/Co(0.6 nm)/W(*t* nm)]$_{N=10}$/MgO(2 nm)/Ta(3 nm) is deposited on SiO_2 substrate by magnetron sputtering. The both DL and FL torque increase with W thickness up to 0.6 nm and have maximum at this specific thickness. The maximum charge-to-spin conversion efficiency in [Pt/Co/W(0.6)]-SL is calculated as ~ 0.42 for the DL-SOT and ~0.59 for the FL-SOT, respectively, which is larger than the conventional heavy metals. Moreover, it turns out that the spin Hall angle in the inversion asymmetric superlattice is larger than that of symmetric case (*i.e.*, [Pt/Co]-SL). Additionally, the Pt thickness is varied in the superalttice of [Pt/Co/W(0.6)] which possesses largest SOT. When the Pt thickness varies in [Pt/Co/W(0.6)]-superalttice, the both DL and FL-SOT are dropped at 2 nm of Pt thickness. The change of the SOT with the thickness variation in W and Pt cannot be explained by the bulk spin Hall effect.

On the other hand, the XRD allows one to investigate the crystalline structure. When the W thickness is varied, the Pt/Co (111) crystallinity deduced from the intensity of Pt/Co (111) peak has a maximum at W(0.6). The trend of crystallinity at the Pt/Co interface observed in [Pt/Co/W]-SL coincides with that of effective spin Hall angle. Moreover, the out-of-plane strain relaxation at the Pt/Co interface is observed when the Pt thickness increases more than 1 nm. This strain relaxation in the out-of-plane direction also matches with the sudden diminished SOT in [Pt(2)/Co/W]-superalttice. Therefore, Pt/Co (111) crystallinity and the accumulated strain due to the different lattice parameter of Pt and Co increase the SOT in [Pt/Co/W]- superalttice. Therefore, it clearly shows that the interface properties affect to the magnitude of SOT which implies that the improved SOT in the inversion asymmetric superlattice can originate from the Rashba-Edelstein effect rather than the bulk spin Hall effect.

The relation between the orbital moment and SOT is studied by utilizing XMCD spectra. The XMCD spectra measured at two distinct angles (0º and 70º) allows us to quantify the orbital moment to the effective spin moment. It is found that the anisotropic orbital hybridization occurs in the superalttice. The 0.6 nm of W insertion maximizes orbital hybridization in the perpendicular direction. The trend of perpendicular orbital hybridization matches with that of SOT. The perpendicular orbital moment and the FL-SOT which is known as the main contribution from the Rashba-Edelstein effect are scaled. It is found out that there is a positive relation between FL-SOT and perpendicular orbital moment. Thus, the SOT enhancement in non-centrosymmetric superalttice is attributed to the anisotropic orbital hybridization, enhancing Rashba-Edelstein effect through asymmetric electronic structure at the interface.