Title: Spin transfer torque effects in nanostructures

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1. Background and purpose of proposed research

Magnetic configurations of magnetic nanostructures can affect the transport of conduction electrons in the nanostructures. A well-known example is the phenomenon of the GMR (giant magnetoresistance). Inversely, magnetic configurations of magnetic nanostructure *can be affected* by conduction electrons in the nanostructures. One example of the inverse effects is the phenomenon of the current-induced magnetization reversal, which is the essence of the STT MRAM (spin-transfer-torque magnetic random access memory).

As demonstrated by these examples, the interaction between conduction electrons and magnetic configurations results in bi-directional effects. This work aims to study these bi-directional effects in magnetic nanostructures.

2. Proposed plan

In magnetic nanostructures, the magnetic exchange interaction is the main source of the interaction between conduction electrons and magnetizations. The interaction can affect both conduction electron dynamics and magnetization dynamics in numerous ways. Among these effects, I will focus on two particular effects; spin transfer torque and spin motive force.

The spin transfer torque (STT) [1,2,3] refers to the torque acting on magnetizations due to the magnetic exchange interaction. When conduction electron spin states are not in a state favored by the exchange interaction, the interaction modifies the spin states by transferring angular momentum from local magnetizations to conductions electrons. Since the interaction conserves the total angular momentum, this transfer of the angular momentum from local magnetizations to conduction electrons implies that there should exist a back-action and local magnetization states should also be modified. The STT is exactly the torque responsible for the back-action.

The spin motive force (SMF) [4] refers to the effective electric field that conduction electrons experience when they travel in magnetic nanostructures with inhomogeneous magnetic configurations. Due to the magnetic exchange interaction, conduction electron spins tend to align themselves with local magnetization directions in order to minimize the magnetic exchange energy. When the magnetic exchange interaction is strong, which is the case in many magnetic systems, this alignment is almost exact, and thus conduction electron spins follow local magnetization configurations adiabatically. When magnetic configurations are not homogeneous, this tendency of the alignment means that conduction electrons should keep adjusting their spin directions as they move along. A nontrivial prediction of the quantum mechanics is that in this kind of adiabatic evolution, electron wavefuctions acquire additional phase, which is the so-called Berry phase. A recent work by Barnes and Maekawa demonstrated that the Berry phase indeed appears in this magnetic nanostructures and showed that the time evolution of magnetic configurations generate an effective electric field or the SMF since the Berry phase changes with time. For given magnetic configurations, the SMF for up electrons (magnetic moment of conduction electrons parallel with local magnetizations) and down electrons (magnetic moment of conduction electrons anti-parallel with local magnetizations) has opposite signs. Thus the SMF is spin-dependent, and in this sense, the effective electric field generated by the Berry phase is different from conventional electric field.

3. Results and discussions

During my 37-day stay at IMR, I have collaborated with Prof. Maekawa's group. We have discussed various phenomena in magnetic nanostructures but most fruitful outcome came from our collaboration on the SMF in magnetic nano-disk with vortex excitations. Thus I will describe below mostly about this result. For other research subjects, only brief mentioning will be given.

As mentioned in the previous section, the SMF arises when inhomogeneous magnetic configurations change with time. From the previous works, it is well-known that the SMF becomes stronger as the rate of temporal change is high and as the length scale over which magnetizations vary is short. A good candidate system that is favored in view of this criterion is magnetic vortices, since magnetizations change in a very short length scale near the vortex cores. Moreover the SMF can become even bigger when vortices change their core directions, which can be induced by applying time-dependent magnetic fields, for instance. The importance of this situation in view of the SMF was recognized by Prof. Maekawa, and numerical calculations on magnetic vortex systems have been under progress jointly by Dr. J. Ohe (a member of Prof. Maekawa group), Prof. Maekawa, and Prof. Barnes at Miami University, USA. When I arrived at IMR, considerable progress had been already achieved by the three researchers. However the connection with the calculated SMF and another spin-related force, Stern-Gerlach force was not completely clear. During my visit at IMR, I did some analytic calculations to clarify the relation between the two forces. Near the end of my stay period, the manuscript on this work had been completed and the work is now under review in Phys. Rev. Lett.

Another research subject that I have invested my effort is the SMF in magnetic tunnel junctions (MTJ) with magnetic dots imbedded in insulating layers in the MTJs. This interesting system has been analyzed briefly by Prof. Maekawa and Prof. Barnes, which appeared in Nature in early March [5] together with experimental results by Prof. Tanaka's group at Univ. of Tokyo. Although qualitative features of the experimental results were already explained, more quantitative calculation was necessary for a more in depth analysis of experimental data. During my stay, I invested my efforts to perform exactly this calculation. The calculation is still under progress and I plan to maintain communications with Prof. Maekawa for continued collaboration on this calculation.

4. Summary and perspective

A solid understanding of the SMF constitutes an important progress towards accurate theories of magnetization dynamics with predictable power. During my stay at IMR, I worked on two research works, one on magnetic vortex systems and the other on magnetic tunnel junction systems, and I believe that these works clarify the role of the SMF in various magnetization dynamics.

References

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