SI01

Spin oscillations in a free molecular magnet

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Applying an external acoustic wave, we study spin oscillations in a magnetic nanoparticle that is free to rotate about its anisotropy axis. Using Hamiltonian of a rotated two-state spin system, we have shown that superposition of spin and rotational states makes a crucial effect on spin oscillations which exhibit quantum beats of the magnetization. In order to study such a beat structure, we compute dynamics of the magnetization by employing a perturbative approach, and discuss conditions under which this novel quantum effect can be generated. The results are expected to be tested in existing experimental techniques.

SI02

Effects of nonlinear spin dynamics on spin pumping

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Spin pumping has garnered significant interest in recent times. Most of the studies of spin pumping have been on systems in which the magnetization dynamics was linear. In nonlinear dynamics, however, large-angle, nonlinear, chaotic dynamics are regularly produced. We explore the nature of spin pumping signals resulting from nonlinear magnetization dynamical phenomenon. The device geometry comprises of a permalloy (Py) layer in contact with a nonmagnetic Pt layer. Magnetization dynamics is produced in the system by an rf signal applied to a coplanar waveguide patterned on top. Spin injected into the Pt is converted, due to the inverse spin Hall effect (ISHE), to a charge current and has been measured across the Pt layer. We will show that the system under study shown some high peaks at certain frequencies. The frequencies at which the peaks occur have been shown to be non-stochastic, even though one would expect them to be stochastic. Also, a frequency shift in the precessional resonant frequency has been observed as a function of the applied power. A similar shift had been previously observed in spin wave nonlinear dynamics in a different configuration. The origin of the peaks and frequency shifts are discussed.

SI03

Sharp spectral linewidth in spin torque oscillator with perpendicular magnetized Co/Pd free layer

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There has been some scientific and practical interest in spin torque oscillator (STO) using perpendicular materials [1]. For application of STO to information-communication nano RF devices, it is important to investigate linewidth properties, although comprehensive understanding of linewidth properties in STO using perpendicular materials is still lacking. In this study, we have measured spin torque oscillation in giant magnetoresistance devices having a Co/Pd extended free layer and a NiFe/CoFe nanomagnet fixed bilayer. The total thickness of Co/Pd is 2.4 nm, and it was confirmed that Co/Pd has perpendicular magnetic anisotropy by vibrating sample magnetometer. Spin torque oscillation was measured under the low in-plane magnetic field using spectral analyzer. Microwave signal induced by spin transfer torque was clearly observed with oscillating frequency at 3.3 GHz. This frequency increased with increasing applied current i.e. positive nonlinear frequency shift. Obtained minimum spectral linewidth was 13 MHz, which is very small, compared with that of previous work on perpendicular materials [2]. Our results suggest that applying the low magnetic field to the Co/Pd film plane is efficient to obtain sharp spectral linewidth. This work was partly supported by Strategic Japanese-German cooperative program (ASPIMATT) from JST and by Japan Society for Promotion of Science.

[1] S. M. Mohseni et al., Phys. Status Solidi RRL 5, 432 (2011). [2] C. H. Sim et al., J. Appl. Phys. 109, 07C905 (2011).

SI04

Clocking schemes for soliton propagation in a ferromagnetically-coupled quantum-dot chain

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Transmission of magnetic signals along the ferromagnetically-coupled quantum-dot chain is an essential property to realize the magnetic quantum cellular automata. In the dot chain, a magnetic signal is represented by a topological soliton with a head-to-head or tail-to-tail state. The soliton is exceptionally stable coming from the topology of the system potential-energy surface, and could be driven by an external magnetic field. In addition to the external field, a global clocking field is used to further control propagation speed. We investigate the effect of the clocking field along the hard axis to vary the propagation speed, together with the local trigger field along the easy axis to initialize the soliton propagation by utilizing micromagnetic simulation. Interestingly, it is found that the required static field to initiate the soliton motion is a little larger than the minimum field to maintain the soliton motion, and only local trigger field is required to initiate the soliton propagation. Furthermore, we reveal the role of the global clocking field in the propagation speed, unexpectedly, the clocking field impedes the soliton motion.

SI05

Spin wave propagation in single crystal Au(001)/Fe(001)/MgO(001) waveguides

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The needs for the development of future computing and information storage devices have led the emerging field of spintronics. Since spin waves can propagate macroscopic distance in ferromagnetic material, they can be used as information carrier. Typically spin wave propagations were investigated using garnet films or permalloy films, both of which have small crystallographic anisotropy. Here we investigated spin wave propagations using spin wave spectroscopy technique [1] in single crystal Fe waveguides with cubic and uniaxial surface anisotropies. The sample, Au(001)-50nm/ Fe(001) / MgO(001)-10nm, were fabricated on MgO(001) substrate using MBE system. We varied thickness of Fe (0.5-20 nm), waveguide width (1-100 μm), and distance of two antennae (0-40 μm). The static in-plane magnetic field was applied perpendicular to waveguide. In this way, magneto-static surface waves were propagated along the ferromagnetic waveguides. The group velocity of spin wave was estimated from the oscillation period in transmission spectra. It was about 8.5 μm/ns in 20 nm thick waveguide under 500 Oe external magnetic field. We found that this value linearly decreases as decreasing the thickness. The contribution of magnetic anisotropies as functions of thickness and width of ferromagnetic layer to the spin waves was also investigated.

[1] V. Vlaminck, et al., Science 322, 410 (2008)

SI06

Microscopic theory on the spin relaxation in an inhomogeneous spin dynamics

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The mechanisms of Gilbert damping in materials with inhomogeneous spin dynamics are more complicate than that with homogeneous spin dynamics (Kittel mode). It is well known that the magnetic impurities contribute to Gilbert damping with Kittel mode, on the other hand, the nonmagnetic impurities don't affect that. Recently, it has become clear that in the presence of spin waves (inhomogeneous dynamics), the nonmagnetic impurities contribute to Gilbert damping constant, α [1]. In this case, α is proportional to square of wave vector q in the limit $q \to 0$. The aim of our study is to clarify the q-dependence of α in the entire q range from microscopic theory. Our model is described by s-d model which consists of localized spins, and conducting electrons. In addition to this, we consider the nonmagnetic and magnetic impurities scattering. We obtain the precise expression of α from the linear response theory. Consequently, we find that α is proportional to 1/q in $k\uparrow - k\downarrow < q < k\uparrow + k\downarrow$ ($k\uparrow,\downarrow$ are Fermi vector each spin) due to the Stoner excitation, and is continuously changed into the form of $\alpha 0 + Aq^2$ in $0 < q < k\uparrow - k\downarrow$. α0 originates from the magnetic impurities scattering while Aq^2 is attributed to both the magnetic and nonmagnetic impurities scattering.

[1]Y. Tserkovnyak, E. M. Hankiewicz, and G. Vignale, Phys. Rev. B 79, 094415 (2009).

POSTER PRESENTATION

July 13 (Fri)

SI07

Ultrafast transfer of spin in a non-collinearly magnetized multilayer

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Femtosecond laser pulses can trigger intriguing dynamic phenomena in magnetic systems such as quenching of magnetization within 100 fs. An effect hardly explored is that due to the laser heating high densities of hot electrons are generated, which can lead to transfer of spin angular momentum across different nano-layers at a femtosecond timescale. By controlling these spin currents, we effectively combine the field of spin-caloritronics with ultrafast magnetization dynamics, providing access to spin-caloritronics at ultimate timescales and a unique opportunity for the development of new spintronic devices. Malinowski et al. [1] showed in a time-resolved MO-Kerr effect experiment that spin-dependent transfer of hot electrons can speed up the demagnetization process. Here, in order to maximize the torque applied by these electrons, we explore laser induced dynamics in a SiOx/Pt/Co/Al(~1 nm)/Co/Al sample with a non-collinear orientation of the magnetization, i.e. an in-plane magnetized top Co- and an out-of-plane bottom Co-layer. We provide a proof-of-principle demonstration of laser-induced spin transfer across the Al spacer layer. The absorbed spin transfer and torque on the magnetization of the receiving layer cause an ultrafast canting of its magnetization, which is experimentally observed as a successively induced GHz-precession of the in-plane magnetized Co layer.

[1] G. Malinowski, F. Dalla Longa, J.H.H. Rietjens, P.V. Paluskar, R. Huijink, H.J.M. Swagten, and B. Koopmans, Nature Phys. 4, 855-858 (2008).

SI08

Investigation of spin wave interference circuit with metallic thin film

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Spin waves are promising phenomenon for the future spintronic devices with low power consumption. For the realization of the spin wave device, we focused on the interference effect of spin waves[1]. Magnetostatic surface wave (MSSW) was excited in a NiFe thin film by applying a continuous RF field. In order to excite and detect MSSW, a pair of asymmetric coplanar wave guides (ACPWs) was fabricated on the NiFe thin film. The MSSW was excited by one ACPW, and its signal was detected by the other ACPW as an induced voltage in a real-time oscilloscope. The advantage of continuous excitation lies in that the MSSW signal becomes stable in time and space, enabling us to sensitively detect the spin wave interference. For the observation of spin wave interference, another strip line was inserted in the middle position between the ACPWs. From ACPWs in both sides of the inserted strip line two different MSSWs having opposite wave vectors were excited. By changing the phase of RF fields, the phase difference between two MSSWs was controlled. Induced voltage signal at the inserted strip line was changed according to the phase difference, indicating that we can observe the interference of MSSWs.

[1] M. P. Kostylev et al., Appl. Phys. Lett. 87, 153501 (2005)

SI09

Current-induced magnetization dynamics of synthetic anti-ferromagnetic free layers

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The spin polarized current-induced magnetization dynamics is studied theoretically in the frame of the drift-diffusion model [1-3] for two different spin-valve (SV) structures: (i) single free layer (SSV) Pol/Cu/FM and (ii) synthetic anti-ferromagnetic free layer (SyAF-SV) Pol/Cu/FM/Ru/FM. In a first step we have analyzed the effect of the angular dependence of the spin transfer torque (STT) on the magnetization dynamics for SSVs. For this four SSVs were considered: SSV1 (Co(3.5)/Cu(3)/Co(3)), SSV2 (Co(3.5)/Ru(3)/Co(3)), SSV3 (Co(3.5)/Cu(3)/Py(3)), and SSV4 (Co(3.5)/Ru(3)/Py(3)). The polarizing layer, Co(3.5), is fixed. We found that these four different structures have different magnitudes and angular dependences of STT leading to different current - magnetic field phase diagrams with different critical values and ranges for dynamics. In the case of SyAF-SVs the drift-diffusion model allows us to take account of not only STT at Cu/FM but also STTs at FM/Ru and Ru/FM interfaces. The corresponding phase diagram is distinct from the one where STT across Ru has not been considered. Hence, this reveals that the STT through Ru considerably affects the dynamics of a synthetic free layer. We discuss the results as a function the strength of the Ruderman-Kittel-Kasuya-Yosida (RKKY)-type exchange interactions through Ru.

[1] A. Brataas, Y. V. Nazarov, and G. E. W. Bauer, Phys. Rev. Lett. 84, 2481 (2000); A. Brataas, Y. V. Nazarov, and G. E. W. Bauer, Eur. Phys. J. B 22, 99 (2001). [2] J. Barnas, A. Fert, M. Gmitra, I. Weymann, and V. K. Dugaev, Phys. Rev. B 72, 024426 (2005). [3] S. W. Lee and K. J. Lee, J. Kor. Phys. Soc. 55, 1501 (2009).

SI10

Magnon excitation studies in strongly correlated electron systems

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WITHDRAWN

SI11

Magnetoplasmonic hybrid nanoparticles

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Magnetoplasmonics is a very promising branch of active plasmonics that uses a magnetic field to modulate plasmon resonance: [1] the field-mediated modulation of the plasmonic response of nanoparticles is expected to have strong implications in light guiding applications on plasmon resonance-based sensing. [2,3] In this paper we show how ordinary gold nanoparticles' optical properties are modified by the magnetic field and describe the origin of such magnetoplasmonic behaviour. Then, using a combined approach with the aid of magneto-optics, magnetometry and x-ray spectroscopy we investigate several routes to increase the response to the magnetic field by adding a magnetic moiety to the gold nanoparticle. We found that when a transition metal oxide is added to the gold core in core@shell and heterodimer geometries, the two materials (magnetic and plasmonic) behave independently, thus giving rise to bifunctional magnetic-plasmonic nanoparticle hybrids. True magnetoplasmonic behaviour is instead found when a higher degree of hybridisation exists between the two moieties, as in the case when metallic magnetic metals are added to the gold moiety, thus achieving an enhancement of the magnetic response of the optical properties and giving rise to a synergic, non-additive spectroscopic signature in the magneto-optical spectrum.

1. V. Temnov et al., Nature Photon., 2010, 4, 107. 2. Anker, J. N. et al. Nature Mater.2008 7, 442. 3. Mayer, K. M., Hafner, J. H. Chem. Rev. 2011, 111, 3828.

SI12

Inhomogeneous standing spin wave excited by the patterned periodic electrode

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There has been a great deal of attention in the spin waves excited in ferromagnetic films because of their various potential applications such as spin-wave-based logic circuit and the interconnection device between the electric and spintronic devices. Efficient excitation and manipulation of the spin wave are important issues for the realizations of practical device applications. Spin wave interference in three dimensional spin structures may enhance the amplitude of the spin oscillation. For this purpose, we here systematically investigated the thickness dependence of resonant frequency of the standing spin wave. We prepared Permalloy films with various thicknesses and excite the standing spin wave by using a periodic nonmagnetic Cu electrode. The resonant frequency of the spin wave was found to increase with the Permalloy thickness. This can be understood by the increase of the non-excited layer around the bottom of Permalloy layer, which induces the effective magnetic field to the excited layer via the exchange interaction. We also perform similar studies of the standing spin wave in the other ferromagnetic structures exchange biased and ferromagnetic/nonmagnetic multi-layered film and present the optimized structure for increasing the output signal induced by the spin wave excitation.