SI13

Observation of spin-waves by time-resolved magneto-optic kerr effect microscope

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Spin-wave is an ordering of the magnetization when the magnetization of a ferromagnet is tilted away from its equilibrium state. The spin-waves in metallic thin films have been recently studied as an emerging field of magnetism for magnetic recording and spintronics devices. The spin-waves can be detected by either electrical or optical method for either frequency or time domain, respectively. In the frequency domain the ferromagnetic resonance has been commonly employed to detect the spin-waves, whereas in the time domain, it is typical to detect damped oscillation of magnetization excited by a short magnetic pulse via an inductive or optical apparatus. Here we report the experimental results on the spin-waves by use of all optical pump-probe method. 20-nm-thick Co thin films are prepared on a GaAs substrate by dc magnetron sputtering. The pump beam is focused onto a spot with a diameter 1 μm of a sample under an applied magnetic field 2 kOe at normal direction of the film surface. The spin-waves are then observed by controlling the tilt angle of the probe beam with a fixed pump beam. Using this method, a propagating spin-wave can be measured directly and further analysis will be discussed.

SI14

Nuclear magnetic resonance study of proton dynamics in ZnO

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Hydrogen acting as a dopant is widely known in compound semiconductors including many oxides. However, in order for such doping to be technologically relevant, the thermal stability of the H-donor must be enough to avoid degradation during device operation at and above room temperature. Here, we have carried out 1H NMR measurements in order to understand proton motions in the ZnO lattice at temperatures between 200 K and 400 K. In our post-annealed ZnO, there are two proton species, one of which can be assigned to protons at interstitial sites (Hi^+) in ZnO. The other species shows no appreciable motion in the temperature range. The distinct activation energies obtained for the Hi^+ motion, 0.27 eV and 0.42 eV, are associated with the reorientation around the bonding oxygen atom and hopping between neighboring oxygen atoms, respectively. These activation energies for diffusion, obtained from the spin-spin relaxation measurements, are in close agreement with those obtained from ab initio calculations.

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SI15

Micromagnetic study of magnonic band gaps in waveguides with a periodic variation of the saturation magnetization

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Spin wave propagation in micro-sized magnonic crystals (MCs) is intensively studied due to their potential technological application for signal processing in spintronic devices. Here we report on micromagnetic simulations [1] of the spin wave propagation in a MC realized as a permalloy ($Ni_{80}Fe_{20}$) waveguide with a periodical variation of its saturation magnetization. In real structures the variation of magnetization can be achieved by using an ion implantation technique. The 2 μm-wide waveguide of 40 nm thickness is magnetized transversal to its long axis. The MC lattice constant is equal to 1 μm. The spin-wave transmission characteristics have been studied as a function of the width of the implanted areas and of the level of the magnetization variation M/M0. Frequency band gaps were clearly observed in the spin-wave transmission spectra. The dependences of the depth, width and the position in frequency and space of the rejection band gaps on the above parameters are referred in our studies. The role of the higher order spin-wave width modes on the MC properties is discussed as well. Support from DFG (grant SE-1771/1-2) is gratefully acknowledged.

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SI16

Spin-transfer induced spin waves of a magnetic point contact with a confined domain wall

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Spin-transfer induced microwave oscillation will be a powerful candidate for applications in future wireless telecommunication technologies. According to Ref. [1], the oscillation of a domain wall between the Bloch- and Neel-type magnetic configurations is induced by a direct current and the corresponding oscillation frequency is proportional to the current density. It is also known that the current injected through a point contact can excite a variety of spin wave modes [2-4]. It is intriguing to ask if such spin wave modes can be excited in a thin magnetic layer connected to a magnetic point contact containing a domain wall. From our calculation we found that three different kinds of spin wave modes can be excited in the thin film depending on the bias current density. The low frequency mode just above the threshold is the propagating spin wave mode. Then the oscillation frequency increases drastically with increasing the current density and reaches more than 100 GHz. At high current density the excited spin wave mode is a propagating mode with a large angle precession. We also found that applied field independence of the frequency for the second mode. We shall discuss the physics behind the excitation of spin wave modes.

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SI17

Spin-torque-nano-oscillator using the perpendicular magnetized CoFeB/MgO/CoFeB magnetic tunnel junctions

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Perpendicular magnetized free layer in the magnetic tunnel junctions (p-MTJs) has advantages for spin-torque-nano-oscillator because coherent precession, high output power, and increasing precession frequency due to high magnetocrystalline anisotropy, can be expected. In this study, the microwave transmission properties were investigated for the p-MTJs using thin CoFeB. The multilayer was prepared by UHV sputtering system and patterned it into 40-nm-sized junctions with coplanar waveguide electrode. The microwave properties were measured under the in-plane magnetic field of 3 kOe to tilt the free layer. The tunnel magnetoresistance ratio was 70% and 0.9% for the out-of-plane and in-plane direction, respectively. Below -0.24 mA, the spin torque noise was observed with broad signal. The STO signal was clearly observed above -0.30 mA at 6 GHz, and the second harmonic signal was not observed due to the single-precession-mode by small junction size. The linewidth and output power was 650 MHz and 1.1 nW, respectively. Power has a potential to be more enhanced by stabilizing the pinned layer to increase the relative angle between free and pinned layer. This study was partly supported by ASPIMATT (JST), by Grant-in-Aid for Young Scientists A (No. 22686001), by FIRST program (JSPS), and by Maekawa-Houonkai foundation.

SI18

Planar approximation for spin-transfer devices with tilted polarizer

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Planar spin-transfer devices with dominating easy-plane anisotropy can be described by an effective one-dimensional equation for the in-plane azimuthal angle [1-3]. Such a description maps the Landau-Lifshitz-Gilbert equation on the Newton equation for the motion of classical particle in a one-dimensional potential and thus provides an intuitive understanding of the magnetic dynamics, allowing one to obtain qualitative results without performing detailed calculations. We apply the effective planar equation to describe magnetic switching and precession states in spin transfer devices with tilted polarizer [4]. The approach allows one to list the possible dynamic regimes, including the precession cycles, and sketch the switching diagram of the device.

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SJ01

Fast SpinRAM simulation by GPU

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Spin transfer torque driven magnetoresistive random access memory (SpinRAM) is one of the candidates of the next generation non volatile memory, and it is studied intensively. Micromagnetic simulation is one of the methods to study it. In the SpinRAM simulation, because the size of the MTJ element is small, the number of the calculation cells is small, and the calculation for one simulation takes only a few minutes. However in the real analysis, more than millions of simulations are repeated with different conditions, the total simulation time becomes huge. Speed up of the simulation is important. Recently, a Graphic Processing Unit (GPU) is used to accelerate the micromagnetic simulation. The acceleration rate strongly depends on the number of the calculation cells, and a huge number of the calculation cells is required to achieve high speed up ratio. Speed up can not be expected in SpinRAM simulation by GPU. In this paper, we propose the simulation method to calculate a number of the MTJ elements in parallel by GPU, and achieve 75 times of the speed up ratio in maximum. This study was supported by New Energy and Industrial Technology Development organization (NEDO) partly.

SJ02

Micromagnetic simulations for the spin dynamics and Gilbert damping constants in nano-dot with perpendicular magnetic anisotropy

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Spin dynamics and the magnetic damping of a nano-dot ellipse with perpendicular magnetic anisotropy (PMA) are presented by the micromagnetic simulations. While the in-plane static magnetic field is applied to the long axis of the ellipse, the small in-plane RF magnetic field is applied to the short axis of the ellipse to mimic the ferromagnetic resonance (FMR) technique. The susceptibility can be obtained by the power spectra of fast Fourier transform (FFT) from magnetizations dynamics. There are two regions in the external static field dependence resonance frequencies for typical PMA system. (I) With small external field, the magnetization is tilted to the static field direction with the finite angle from the film normal. (II) If the static field is strong enough, the magnetization is aligned to the static field, where the Zeeman energy overcomes the PMA energy. In this simulation, the extract Gilbert damping constants from the line widths of the resonance peaks from two different regions. Surprisingly enough, the obtained values (α_I = 0.0165 and α_II = 0.0194) are different from the input value (α = 0.027). It implies that the experimentally obtained α can be different from the real values.

SJ03

Micromagnetic study on micro-structured ferromagnetic thin film for high frequency device applications

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The ferromagnetic metallic thin films of Fe has been considered as promising materials for on-chip microwave devices, owing to the much higher saturation magnetization Ms compared with a conventional material of yttrium iron garnet (YIG). Understanding of demagnetizing effects, related to Ms, is important for the design of micro-structured devices with the high Ms material[1]. In the present study, geometrical effects of micro-structured magnetic thin films on high frequency magnetic properties are numerically investigated with micromagnetic simulations. The standard material parameters of Fe with cubic anisotropy are assumed in the simulation. The values of μ' (@ 1 GHz) and the resonance frequency fFMR for various aspect ratios w/t are compared. The increase of μ' with the decrease of w/t is attributable to the size effect in fFMR, related to the demagnetizing coefficient along the film normal direction. It should be noticed that the μ' for the same w/t with different w and t is identical. The results suggest that the demagnetizing effect on the high frequency magnetic properties becomes prominent for the w/t smaller than 400 in the structured Fe thin film.

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SJ04

Atomistic modelling of magnetization dynamics with spin torque

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The dynamics of the magnetization following the introduction of a spin current is studied by using an atomistic model coupled with spin accumulation. The evolution of the magnetization and spin accumulation in a trilayer system are calculated self-consistently, the interaction between magnetisation and spin current provided by an s-d exchange term. A spin-polarised current is introduced into the system containing a domain wall whose width is varied by changing the anisotropy constant. The magnetisation is calculated using an atomistic model based on the Heisenberg exchange energy and spin dynamics introduced via the Landau-Lifshitz-Gilbert equation. The net spin torque contributes two important components: the adiabatic (AST) and nonadiabatic torques (NAST). We show that both arise naturally when calculated directly from the spin accumulation. The maximum value of the AST and NAST are considered for each thickness of domain wall. Both torques decrease as the domain wall thickness increases. The nonadiabaticity factor, defined as the ratio of the NAST and AST is also shown. Increasing the domain wall thickness gives rise to a small angle between magnetisation in domain wall. Interestingly the degree of NAST tends to decay to zero as the thickness of DW increases relative to the spin diffusion length.

SJ05

Highly parallelized micromagnetic simulator using fast multipole method

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We have developed an alternative method for computing the magnetostatic field of arbitrary-shaped ferromagnetic systems instead of fast Fourier transform (FFT). The method is based on the Taylor expansion of the potential, as is required by the fast multipole method (FMM)[1][2], the most efficient method known for calculating mangnetostatic fields in very large systems. The FMM scales as O(N) in both time and space complexity compared to the direct method with $O(N^2)$, or FFT with O(N logN)[3] and even easier to be parallelized, which is a more valuable solution for larger ferromagnetic systems. Graphical processing units (GPU) are now increasingly viewed as data parallel compute coprocessors that can provide significant computational performance at low price[4]. We have developed a micromagnetic simulator using the parallelized method with GPU and have tested in various configurations. In that case speedups of over a factor 100X can easily be obtained compared to the CPU-based OOMMF[5] program developed at NIST. The tests are carried out with μMag Standard Problem[6] #1,#2,#3,#4.

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SJ06

Effect of calculation conditions on the numerical simulation of magnetic materials with random magnetic anisotropy

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Numerical simulation was performed on magnetic materials with random anisotropy. An assembly of magnetically interacting grains with randomly oriented uniaxial anisotropy was provided and magnetization was calculated using the Landau-Lifshitz-Gilbert equation. The magnetization in a particular grain is assumed to align in the same direction (single spin model).[1] Calculations were carried out for N × N × N three dimensional cells changing cell sizes from 5 to 40 nm. The interaction at the interface between grains was taken into account by the interaction energy between the unit vectors representing grain magnetization directions. N was changed from 10 to 64. In the case of N = 10, the relation between coercive forces and grain sizes was obtained to be δ = 5.7 in Hc ~ D^δ, and fits to the primitive theory of random anisotropy model (RAM) δ = 6. As the N increased, the δ tends to decrease slightly from 5.7 to 4.2. The grain sizes where the coercive force becomes less dependent on the grain size, suggesting the natural exchange length, did not changed much.

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