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Stochasticity and bifurcation in spintronics device for probabilistic computing

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Abstract– Physics of the stochastic behavior of spintronics devices for probabilistic computing is discussed. We experimentally access the potential landscape of nanoscale stochastic magnetic tunnel junctions (MTJs) perturbed under spin-transfer torque (STT) and magnetic field, and discuss the result based on the local bifurcation theory. In addition, we discuss a design guideline of the switching event time for the faster operation of the probabilistic computing and its relation to the fluctuation-dissipation theorem. Based on the guideline, we demonstrate the nanosecond relaxation time of the nanoscale stochastic MTJ device.

1. Introduction

Recently, stochastic MTJs, which have a small energy barrier between two states of the free layer magnetization direction, gather much attention for the applications of spintronics-based unconventional computing such as invertible logic and probabilistic computing [1, 2]. Their probabilistic bit (p-bit) state in the MTJs is controlled by STT, and rigorous understandings of (1) the STT modulation of the potential landscape and (2) the physics governing the switching event time between the states are highly required.

Here, in the first part of this paper, we experimentally access the potential landscape under STT and magnetic field in the nanoscale stochastic MTJs by carefully combining random telegraph noise, ferromagnetic resonance, and switching probability measurements, and discuss the results in terms of the classification of the local bifurcation type of the pseudopotential under external fields [3]. In the second part of this paper, we show a way to reduce the relaxation time of the thermal magnetization reversal with a numerical simulation based on the stochastic Landau-Lifshitz-Gilbert (LLG) equation. By introducing *relative entropy* into the Fokker-Plank equation of the probability density distribution of the magnetization direction, we show design guidelines for the faster relaxation time and discuss their relation to the fluctuation-dissipation theorem [4]. Based on the guideline, we fabricate the stochastic MTJ devices and demonstrate their nanosecond relaxation time [5].

2. Switching of local bifurcation type of the potential landscape under STT

We fabricate a stack with synthetic ferrimagnet/ CoFeB(1.0)/ MgO(1.0)/ CoFeB(1.88)/ Ta(5)/ Ru(5) (numbers in parenthesis are thickness in nm) [3]. The top 1.88-nm-thick CoFeB layer is a free layer with a perpendicular easy axis. The stack is processed into a stochastic MTJ with a diameter of 34 nm. The tunnel magnetoresistance ratio of the stochastic MTJ is 73%, which enables us to measure the switching of the magnetization through its random telegraph noise. The distribution of the number of switching event times shows the exponential distribution, indicating the thermal fluctuation is characterized by a Poisson process. We determine the relaxation time as 3 ms from the distribution. The effect of the STT on the thermal stability factor $\Delta(V)$ has been phenomenologically described by an equation $\Delta(V) = \Delta(0)(1-V/V_{C0})^n$, where V_{C0} is the critical voltage for the STT switching, and n is the switching exponent. By combining ferromagnetic resonance, random telegraph noise, and switching probability measurements under various voltage and magnetic fields, we clarify that n changes from 2 to 3/2 with changing V. We show that this behavior is well explained by the change of the local bifurcation structure of the pseudopotential under STT from pitch-fork bifurcation to saddle-node bifurcation [3].

3. Nanoseconds operation of the stochastic MTJ

The faster relaxation time of the stochastic MTJ offers a faster calculation speed of probabilistic computing. We investigate the magnetization dynamics of the stochastic MTJ with the numerical simulation based on the LLG

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equation with the Langevin term. We find that in-plane stochastic MTJs have several orders shorter switching times than perpendicular stochastic MTJs even when they have the same energy barrier. To discuss the relaxation of the magnetization direction distribution quantitatively, we introduce the *relative entropy* of the probabilistic distribution of the magnetization direction. We show the switching probability is a one-to-one function of the relative entropy, which initially takes a positive value and reduces to zero when the distribution completely relaxes to the Boltzmann distribution after infinite time. With the Fokker-Planck equation, we derive an analytical description of the reduction speed of the relative entropy and find that the reduction is faster when the precession is faster and/or the damping constant is larger, indicating that the relaxation time is shorter when "energy relaxation" is faster. We discuss this correlation between relaxations of the state and the energy in terms of the fluctuation-dissipation theorem in nanoscale magnets.

In general, in-plane easy MTJs have much larger precessional frequencies than those with perpendicular easy axis due to the large demagnetizing field, which reasonably explains the difference in the switching time shown by the LLG equation between in-plane and perpendicular stochastic MTJs. Guided by the theoretical predictions, we fabricate stochastic in-plane MTJs. A stack structure consisting of Ta(5)/ PtMn(20)/ Co(2.6)/ Ru(0.9)/ CoFeB(2.4)/ MgO/ CoFeB(2.1)/ Ta(5)/ Ru(5) is processed into elliptic MTJs with a geometrically averaged diameter of ~ 100 nm. The top CoFeB(2.1) layer is a free layer with an in-plane magnetic easy axis with the perpendicular effective anisotropy field of −0.46 T, which gives 2-3 orders larger precession frequency than that of stochastic perpendicular MTJs. We measure the random telegraph noise of the stochastic in-plane MTJs and observe the relaxation time down to 8 ns, which is more than 5 orders of magnitude shorter than that of typical stochastic perpendicular MTJs and about 100 times faster than the shortest relaxation time of in-plane MTJs reported so far [5].

4. Conclusion

We have investigated the stochastic behavior of the MTJ for efficient probabilistic computing by elucidating the potential landscape under external fields and the relaxation time of the stochastic MTJs. We have also found that these properties of the stochastic MTJs are closely related to the local bifurcation structure and fluctuation-dissipation theorem, respectively, suggesting the possible application of the stochastic MTJs as an experimental platform of modern statistical physics.

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