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Spin Transfer Switching in Perpendicularly Magnetized GMR Nanopillars in both Dynamic and Thermally Assist Regimes

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1. Introduction

Magneto-resistive random access memory using spin transfer switching (STS) [1], so called Spin-RAM, is researched as next generation memory because of its high speed switching and low power consumption. Especially, spin-RAM with perpendicularly magnetized films is promising because of its large anisotropy and high thermal stability [2] [3]. Modes of STS are divided into dynamic switching [4] and thermally assist switching [5]. However, unified understanding of the dynamics in both regimes has not been achieved yet. In this paper, we report the STS properties in giant magneto-resistive (GMR) nanopillar with perpendicular magnetization.

2. Experiments and results

Sample

In our research, the film structure is as follows: substrate / buffer layer / [Co(0.3) / Pd(1)]9 / Au(4) / [CoFe(0.5) / Pd(1) / CoFe(0.5)] / cap layer (nm in thickness). The bottom Co / Pd multi layers work as a reference layer. The film was patterned into cylindrical nano-pillar junctions with the dimensions of 100 nm. The MR curves are shown in figure 1. The magneto-resistance (MR) ratio is 0.47%.

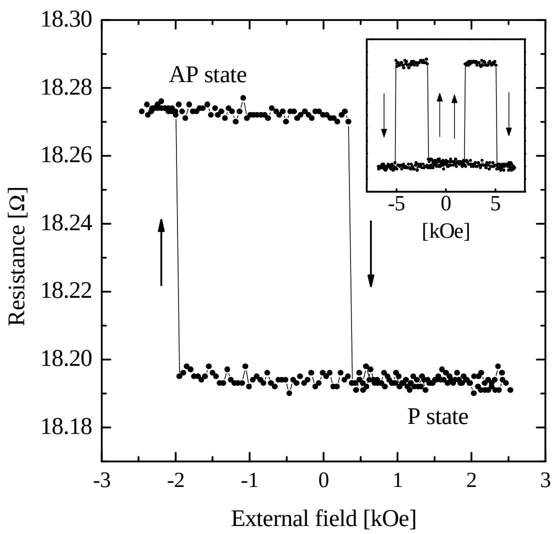

Fig. 1 The dependence of the resistance (R) curve (minor loop) on external magnetic field (H_{ext}). Inset shows full loop of R-H_{ext} curve. Coercively of free and reference layer are 1.3 kOe and 6.0 kOe, respectively. Offset field originated from the dipole coupling between free and reference layers is –0.7 kOe.

Measurement

To evaluate STS probability (P_{sw}), measurement was carried out in the following procedure.

(1) The devise is reset to anti-parallel (AP) state by applying a negative pulse.
(2) The device state is confirmed by measuring the resistance.
(3) Applying a positive trial pulse with width (t) and height (I) to the device to induce STS in the device.
(4) The final state of the device is monitored by measuring the resistance.

By repeating this procedure 100 times per each trial pulse condition, we evaluated the STS probability. Figure 2 shows points of P_{sw} = 0.5 from AP to parallel (P) state.

Analysis

Generally, the equations proposed by Sun [6] and Li [7] are used for analysis of STS. However, these equations can be used only in the limit of long and short t. We propose new models which can be applied in wider range of time.

The dynamics of the magnetization in the free layer under magnetic field is shown by LLG equation including spin-transfer torque as follows,

$$\frac{d\mathbf{S}_2}{dt} = \gamma \mathbf{S}_2 \times \left(\mathbf{H}_{eff} + \mathbf{H}_{stochastic}\right) - \alpha \mathbf{e}_2 \times \frac{d\mathbf{S}_2}{dt} + g(\theta)\frac{I}{-e}\frac{\hbar}{2}\mathbf{e}_2 \times \left(\mathbf{e}_1 \times \mathbf{e}_2\right), \quad (1)$$

where γ, $\mathbf{S}_2$, $\mathbf{H}_{eff}$, $\mathbf{H}_{stochastic}$, α, $\mathbf{e}_1$, $\mathbf{e}_2$, e, $\hbar$, and $g(\theta)$ mean gyro magnetic ratio of an electron (–0.0185 GHz/Oe), the spin in the free layer, effective field, random field by thermal effect, damping constant, the unit vector of the spin in the reference layer, the unit vector of $\mathbf{S}_2$, elementary charge (1.602×10^{-19} C), Dirac constant (1.05×10^{-34} Js) and the spin transfer efficiency.

When I is larger than the critical current at room temperature (I_{c0}), the STS process is non-adiabatic, so called dynamic switching. In this regime, the expression of STS probability is described as follows,

$$P_{sw}(t) = \exp\left[-4\, f(h) \varDelta\, e^{\,2\Omega(1-h)t}\right],$$

$$f(h) = \left(\frac{h-1}{2h}\right)^{\frac{2}{1+h}},\ h = \frac{I}{I_{c0}},\ \varDelta = \frac{\mu_0 M_2 H_u}{2k_B T}, \tag{2}$$

where $\varDelta$, M_2 and H_u are the thermal stability, the magnetization of the free layer times volume and uniaxial anisotropy. Then, we suppose the initial angle of $\mathbf{S}_2$ follows Boltzmann distribution.

On the other hand, the STS process in the condition of $I < I_{c0}$ is helped by thermal effect, so called thermally assist switching. The dynamics is expressed by the Fokker-Planck equation, which is described as equation (3).

$$\frac{\partial p(z,t)}{\partial t} = \frac{\partial}{\partial z}\left[\frac{\alpha}{S_2}\left(1-z^2\right)\left(\frac{\mathrm{d}E_{\mathrm{eff}}(z)}{\mathrm{d}z} + k_B T \frac{\partial}{\partial z}\right)p(z,t)\right],$$

$$E_{\mathrm{eff}} = -\frac{\mu_0 M_2}{2} H_u z^2 + \frac{1}{\alpha}\frac{\hbar}{2}\frac{I}{e}\int g(z)\mathrm{d}z\ , \tag{3}$$

where μ_0 and z are space permeability ($4\pi\times10^{-7}$ H/m) and the coordinate normal to the plane. From this equation (3), the STS probability is derived as follows [8][9],

$$P_{sw}(t) = 1 - e^{-t/\tau_{\mathrm{SW}}},$$

$$\tau_{\mathrm{sw}} \approx \tau_0\, e^{\varDelta(1-h)^2},\ \ \tau_0^{-1} = \Omega\sqrt{\frac{\varDelta}{\pi}}(1+h)(1-h)^2, \tag{4}$$

$$\Omega = \alpha(-\gamma)H_u\,.$$

If we only consider the case of P_{SW} = 0.5, equations (2) and (4) fit the experimental result by three independent parameters as follows,

$$\varDelta = 80,\quad I_{c0} = 1.66\ \mathrm{mA},\quad \Omega = 1.65\ \mathrm{GHz}.$$

Moreover, we confirmed that these parameters satisfy the experimental result in the middle regime between thermal assist and dynamic regime by macro-spin simulation (shown in figure 2). In the macro-spin simulation, we used the designed value of Ms and the values obtained by spin-torque diode effect as the parameters.

3. Conclusions

We investigated spin transfer switching properties in a perpendicularly magnetized GMR nanopillar. The probability of spin transfer switching as the function of the height and width of incident pulse is discussed in dynamic and thermally assist switching regimes. To explain the experimental results, we re-developed the model equations. Newly obtained expressions well explained experimental results both in dynamic and thermally assist switching regimes using common set of parameters.

Acknowledgements

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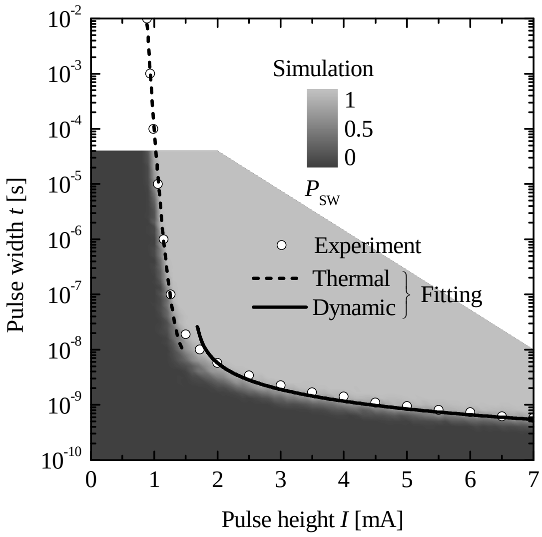

Fig. 2 Comparison of the experimental result with the macro-spin simulation. Vertical axis is logarithmic scale of t. Light (dark) ash color in the figure represents high (low) P_{sw} value by macro-spin simulation. White circles show points of P_{SW} = 0.5 in experimental result shown in figure 2. Black continuous (dotted) line shows fitting result for P_{sw} = 0.5 by equation (2) in $I > I_{c0}$ (equation (4) in $I < I_{c0}$).

References

[1] J. C. Slonczewski, J. Magn. Mgn. Mater., **159**, L1, (1996).

[2] S. Mangin, D. Ravelosona, J. A. Katine, M. J. Carey, B. D. Terris, and E. E. Fullerton, Nat. Mater., **5**, 210, (2006).

[3] A. D. Kent, B. Özyilmaz, and E. del Barco, Appl. Phys. Lett., **84**, 3897, (2004).

[4] A. A. Tulapurkar, T. Devolder, K. Yagami, P. Crozat, C. Chappert, A. Fukushima, and Y. Suzuki, Appl. Phys. Lett., **85**, 5358, (2004).

[5] M. P. Sharrock, J. Appl. Phys., **76**, 6413, (1994).

[6] J. Z. Sun, Phys. Rev. B, **62**, pp. 570-578, (2000).

[7] Z. Li. And S. Zhang, Phys. Rev., **130**, 1677, (1963).

[8] Y. Suzuki, A. A. Tulapurkar and C. Chappert, "*Nanomagnetism and spintronics Chapter3 T. Shinjo eds.*", Elsevier Science, (2009).

[9] T. Taniguchi and H. Imamura, Phys. Rev. B, **85**, 184403, (2012).