Strain/Stress-Assisted Spin Transfer Torque Effects Using Phase Field And Micromagnetic Methods

Houbing Huang[1, 2], Jiamian Hu[1], Xingqiao Ma[2], and Long-Qing Chen[1]

[1]*Pennsylvania State University, University Park, PA 16802, USA*

[2]*University of Science and Technology Beijing, Beijing, 100083, China*

Introduction

Spin transfer torque (STT) effect arises from the transfer of angular momentums from the electrons of the spin-polarized current to the local ferromagnet when a current goes through a spin-valve nanopillar.

One of the most attractive applications is high density magnetic random access memory (MRAM). However, the high critical switching current J_c of STT-MRAM has to be reduced for achieving the compatibility with highly scaled complementary metal-oxide-semiconductor technology. Another application called spin torque nano-oscillators (STNO) has various attractive advantages, e.g., high frequency microwave (2 GHz~100 GHz), and narrow output band with high Q values >10 000. However, increasing output power is a difficult technical challenge that needs to be overcome for any useful application.

The aim of this work is to understand the effects of strain/stress on the magnetization dynamics using the phase-field method and micromagnetic simulation. We decrease significantly the critical current density and propose an effective method of using stress to adjust the magnetization precession frequency.

Methods and Materials

The magnetization dynamics is described by a generalized Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation, which can be written as

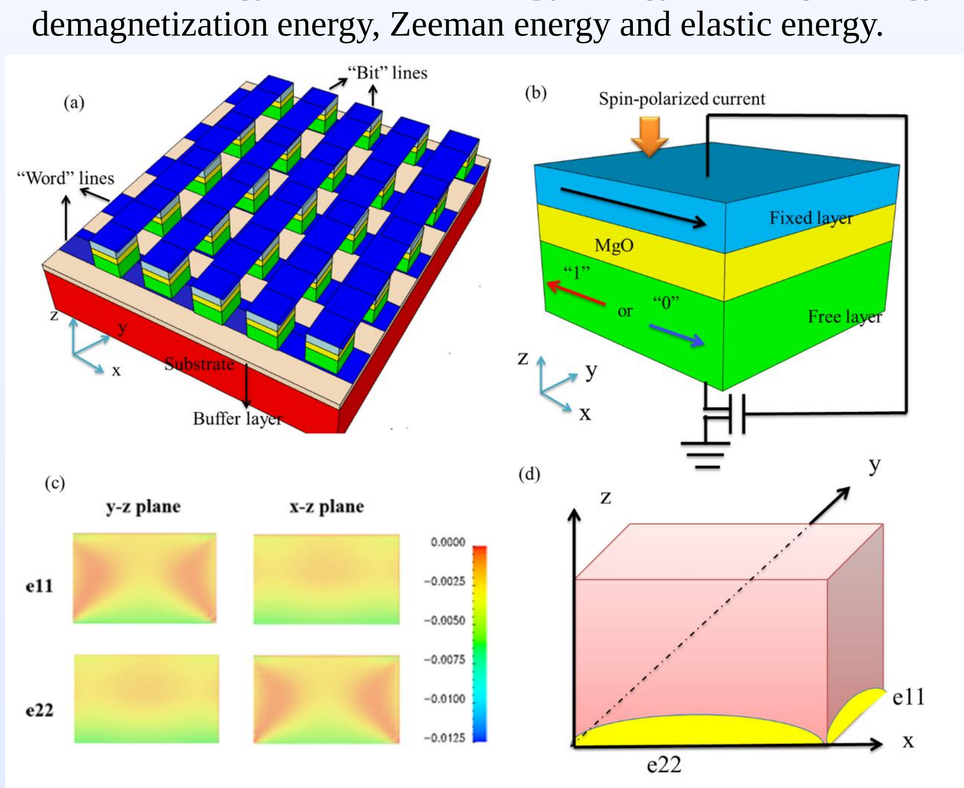
$$\frac{d\mathbf{M}}{dt} = -\gamma' \mathbf{M}\times\mathbf{H}_{eff} - \frac{\alpha\gamma'}{M_s}\mathbf{M}\times(\mathbf{M}\times\mathbf{H}_{eff}) - \frac{2\mu_B J}{(1+\alpha^2)edM_s^{3}} g(\mathbf{M},\mathbf{P})\mathbf{M}\times(\mathbf{M}\times\mathbf{P}) + \frac{2\mu_B \alpha J}{(1+\alpha^2)edM_s^{2}} g(\mathbf{M},\mathbf{P})(\mathbf{M}\times\mathbf{P})$$

where $\mathbf{M}$ is the magnetization of the free layer, $\mathbf{P}$ is the magnetization of the pinned layer, $\mathbf{H}_{eff}$ is the effective field, $\gamma'=\gamma/(1+\alpha^2)$, γ is the electron gyromagnetic ratio, and α is the dimensionless damping parameter. μ_B, J, d, e, M_s, are the Bohr magneton, the current density, the thickness of the free layer, the electron charge and the saturation magnetization, respectively. The effective field, total energy and elastic energy could be expressed by,

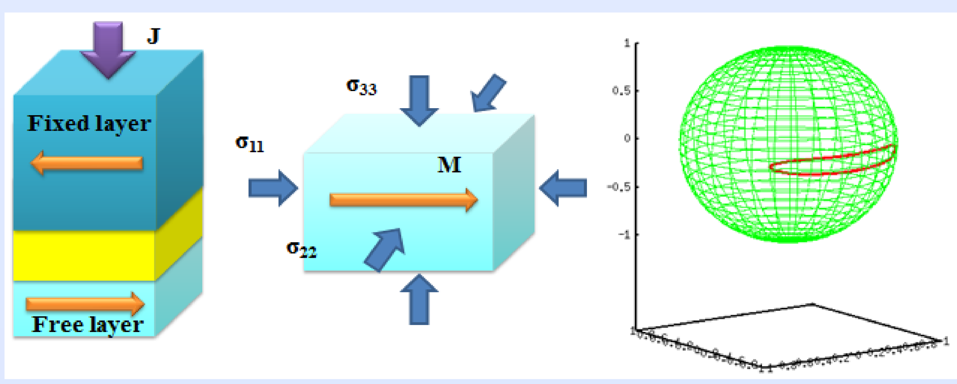
$$\mathbf{H}_{eff} = -\frac{1}{\mu_0}\frac{\delta E}{\delta \mathbf{M}} \qquad E = E_{ani} + E_{exch} + E_{ms} + E_{ext} + E_{elas}$$

$$E_{elas} = \int \frac{1}{2} c_{ijkl}(\varepsilon_{ij} - \varepsilon_{ij}^{0})(\varepsilon_{kl} - \varepsilon_{kl}^{0})dV$$

The total energy includes anisotropy energy, exchange energy, demagnetization energy, Zeeman energy and elastic energy.



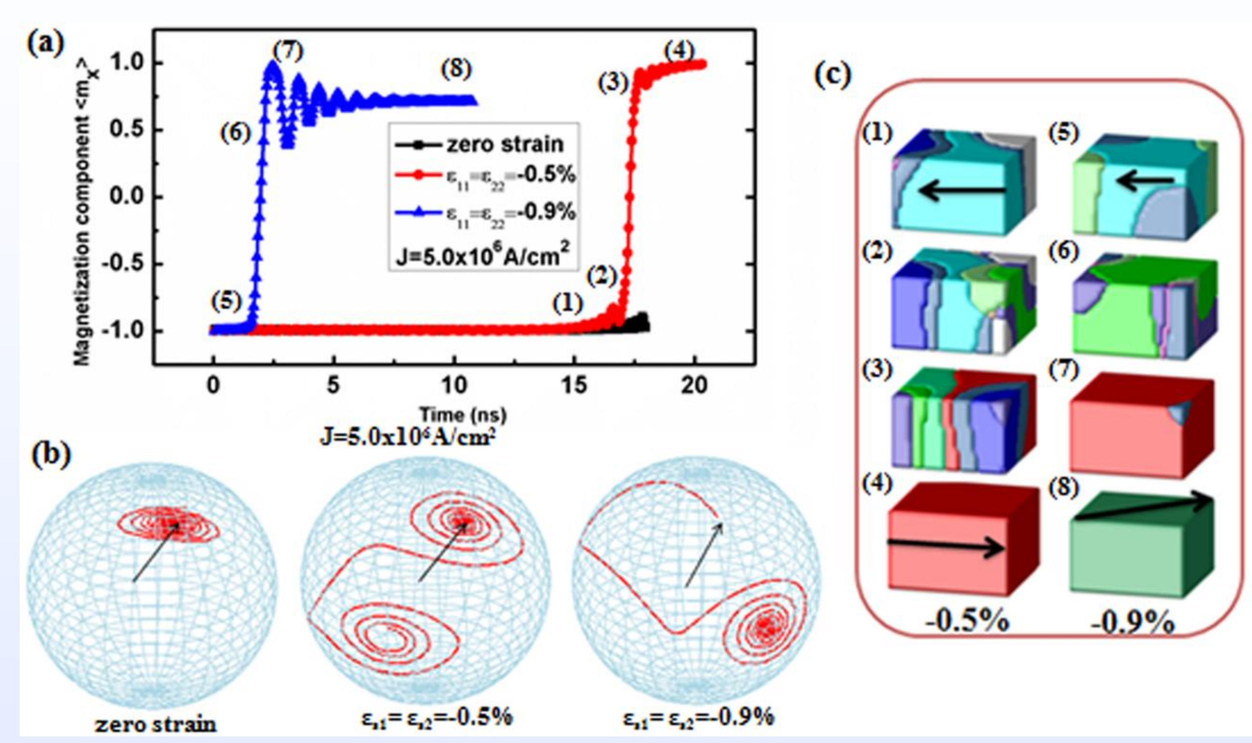
(a) Schematic illustration of strain-induced STT-MRAM (b) Single magnetic tunnel junctions (MTJ) spin valve (c) Strain distribution (d) Schematic illustration of strain distribution.



(a) Schematic illustration of spin valve (b) free layer under external stress (c) magnetization precession trajectory.

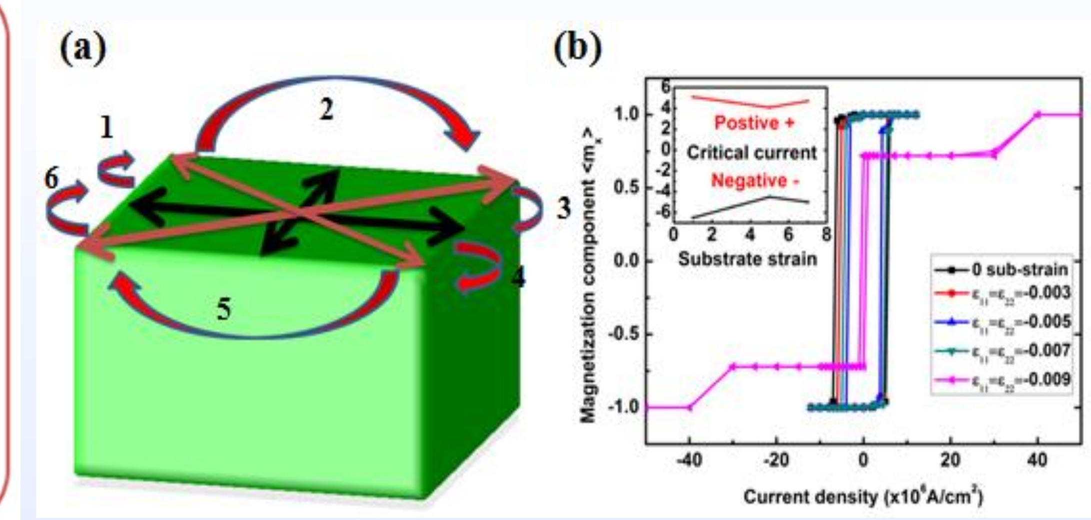
Results and Discussions

Strain-assisted spin transfer torque magnetization switching



(a) The temporal evolutions of the average normalized magnetization components $<\mathbf{m}_x>$ with different substrate strain and (b) Snapshots of magnetic domains evolution with different substrate strain.

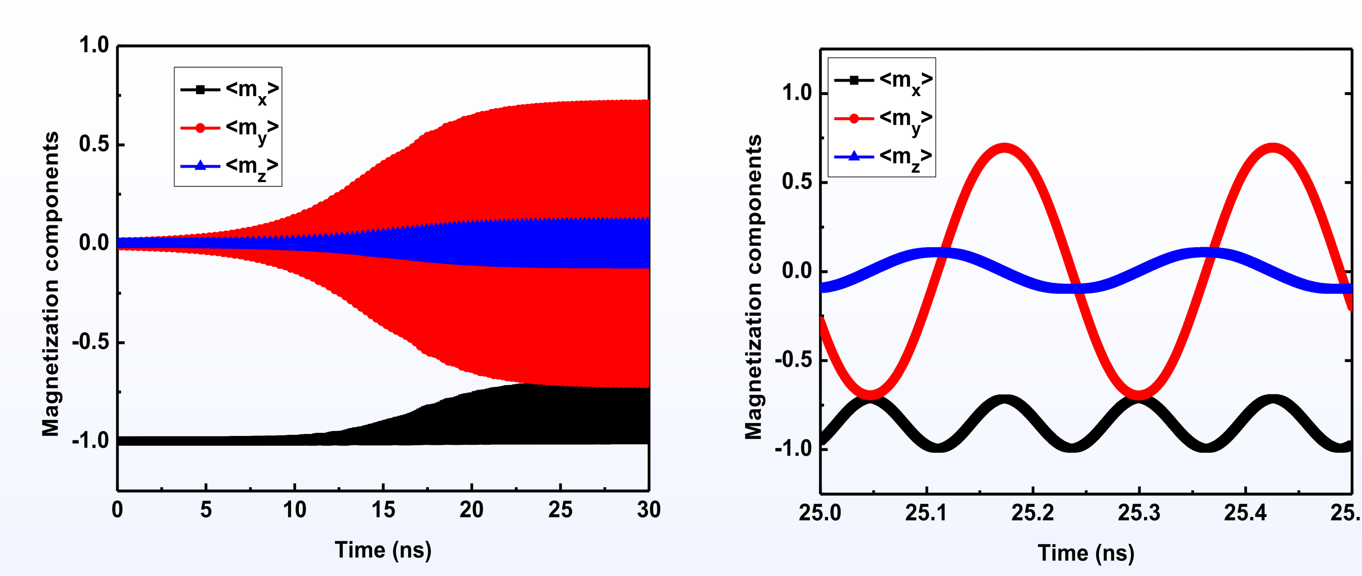
Lower J_c and multicell memories by using misfit strain



(a) Illustration of strain-induced spin transfer switching process (b) substrate strain dependence of resistance versus current density (R-J) curves. Inset shows the critical current densities as a function of substrate strain.

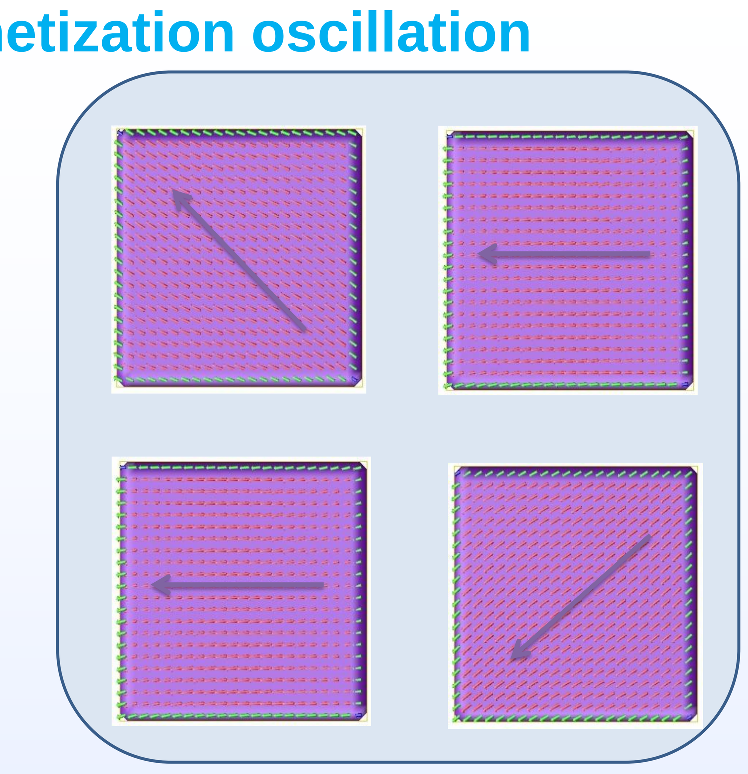
Multicell spin transfer switching

Stress-assisted spin transfer torque magnetization oscillation

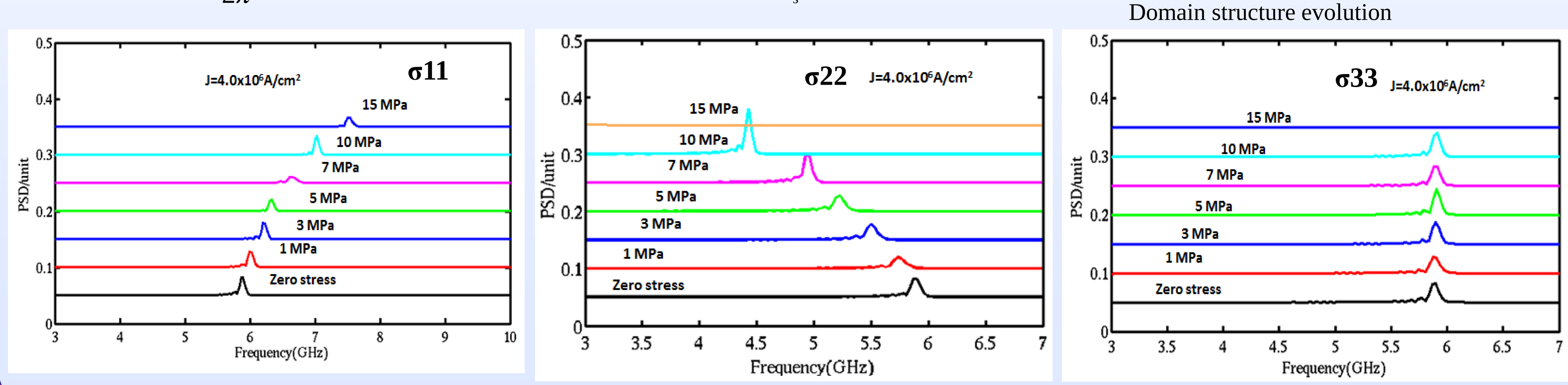


Magnetization evolution

$$f = \frac{\gamma}{2\pi} 4\pi M_s < m_z > \qquad f \approx \frac{\gamma}{2\pi}\left[\frac{\hbar}{2e}\frac{g(\eta)}{M_s d}\right]\frac{J}{\alpha}$$



Domain structure evolution



Magnetization precession frequency dependent on the external stress

Conclusions

We investigated strain-assisted spin transfer switching in CoFeB-based magnetic tunnel junctions by combining phase field simulations with micromagnetic simulations. An effective method of strain-assisted spin transfer magnetization switching is proposed to reorient the magnetization instead of using an external magnetic field. We also proposed an effective method of using external stress to control the magnetization precession in spin torque oscillator instead of the external magnetic field. Our simulations show that the frequency is linearly increasing with the x-axis external stress, and decreasing with the y-axis external stress. In addition, the oscillation frequency is not influenced by the z-axis external stress.

References

[1] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[2] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[3] H. Sukegawa, S. Kasai, T. Furubayashi, S. Mitani, and K. Inomata, Appl. Phys. Lett. 96, 042508 (2010).
[4] R. Okura, Y. Sakuraba, T. Seki, K. Izumi, M. Mizuguchi, and K. Takanashi, Appl. Phys. Lett. **99**, 052510 (2011).
[5] H. B. Huang, X. Q. Ma, Z. H. Liu, F. Y. Meng, S. Q. Shi, and L. Q. Chen, J. Magn. Magn. Mater. 330 16-20 (2013).
[6] H. B. Huang, X. Q. Ma, Z. H. Liu, F. Y. Meng, Z. H. Xiao, P. P. Wu, S. Q. Shi, and L. Q. Chen, J. Appl. Phys. 110, 033913 (2011).
[7] H. B. Huang, X. Q. Ma, Z. H. Liu, C. P. Zhao, S. Q. Shi, and L. Q. Chen, Appl. Phys. Lett. 102, 042405 (2013).
[8] H. B. Huang, X. Q. Ma, Z. H. Liu, S. Q. Shi, and L. Q. Chen, AIP Advances. 3, 032132 (2013).

For Further Information

Please contact *huh18@psu.edu* or *houbinghuang@gmail.com* . More information on this and related projects can be obtained at http://www.ems.psu.edu/~chen/ or http://www.mmm.psu.edu.

Acknowledgments

This work was sponsored by the National Science Foundation of China (11174030), by the US National Science Foundation under the grant number DMR-1006541. The computer simulations were carried out on the LION and Cyberstar clusters at the Pennsylvania State University.