Research Article

Micromagnetic Simulation of Strain-Assisted Current-Induced Magnetization Switching

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We investigated the effect of substrate misfit strain on the current-induced magnetization switching in magnetic tunnel junctions by combining micromagnetic simulation with phase-field microelasticity theory. Our results indicate that the positive substrate misfit strain can decrease the critical current density of magnetization switching by pushing the magnetization from out-of-plane to in-plane directions, while the negative strain pushes the magnetization back to the out-of-plane directions. The magnetic domain evolution is obtained to demonstrate the strain-assisted current-induced magnetization switching.

1. Introduction

Since Sun et al. [1] and Sun et al. [2] proposed the spin transfer torque (STT) effects in the ferromagnetic materials, STT has attracted great attention due to its potential applications of magnetic devices in the past decades [3–8]. In STT effects, angular momentums of the electrons may transfer to the ferromagnetic magnetization. There are three major effects in STT driven magnetization dynamics: (1) current-induced magnetization switching [9–12], (2) current-driven magnetization oscillations [4, 13, 14], and (3) current-driven domain wall motion [15–20]. The current-induced magnetization switching is used in the application of magnetic random access memory (MRAM), which has the advantage of large storage density, high switching speed, low energy consumption, and avoidance of cross writing. The current-induced magnetization switching also eliminates crosstalk between neighboring cells during writing [21]. Furthermore, STT-MRAM has practically unlimited endurance and requires less energy and is faster than conventional magnetic field control MRAM. However, the high critical switching current density J_c of STT-MRAM has to be reduced to achieve the compatibility with the metal-oxide-semiconductor technology.

There are many attempts to reduce J_c for magnetization switching, for example, using CoFeB as the free layer to

reduce the saturation magnetization M_s [22]; using a double spin-filter structure [23] and an antiferromagnetic pinning structure [24] or inserting a Ru spin scattering layer to increase spin scattering [25]; using a composite free layer consisting of two ferromagnetic layers with various coupling types [26–28]; or using Heusler-based spin valve nanopillar [29]. In magnetic thin films, the strain can be effectively utilized to tune the magnetic domain structures [30–33]. For example, the magnetization can be switched between an in-plane and out-of-plane orientation under isotropic biaxial in-plane strains [34, 35] or rotate within the film plane under anisotropic biaxial in-plane strains [36]. Recently, Pertsev and Kohlstedt [37] demonstrated that the critical current density needed for 180° magnetization switching in the free magnetic layer of a spin valve can be reduced drastically by the assistance of substrate misfit strain based on the thermodynamic calculation. Thermodynamic calculation minimizes the total free energy to obtain homogeneous magnetization distribution, but micromagnetic simulations provide the microstructure evolution of magnetization switching. The conventional micromagnetic simulations do not take account of such elastic effect and thus cannot be employed to investigate the assistance of substrate misfit strain in STT induced magnetization switching.

In this paper, we combined the phase-field microelasticity theory with micromagnetic simulations to illustrate misfit

strain which causes the decrease of the critical current density for magnetization switching. In particular, we investigated STT induced 180° magnetization switching in CoFeB magnetic tunnel junctions based on the misfit strain induced 90° magnetization switching [38]. Firstly, we discussed our results by using a hysteresis loop to show the decrease of critical current density. Then, we discussed the effect of substrate strain assistance in STT induced magnetization switching by showing magnetization and magnetic domain evolutions.

2. Model Description

As shown in Figure 1, we investigate the spin valve nanopillars with the structure of CoFeB (2 nm)/MgO (2 nm)/CoFeB (16 nm) of square cross-sectional area ($80 \times 80 \text{ nm}^2$). A Cartesian coordinate system is employed and the current is along the z -axis. A thin MgO layer separates the two CoFeB layers, and the bottom CoFeB layer is the free layer. A spin-polarized current drives the magnetization dynamics of free layer. The top CoFeB layer is the fixed layer with its magnetization vector $\mathbf{P}$ along the positive z -axis. The initial magnetization vector $\mathbf{M}$ of the layer is along the negative or positive z -axis. The lateral length of the free layer of spin valve is fully constrained by a stiff substrate. We generally define the substrate strain ε_{ii} ($i = 1, 2$). The positive current is defined as electrons flowing from the fixed layer to the free layer. In the bottom, a ferroelectric (FE) layer is used to adjust the output strain. In this paper, the positive current will lead to the parallel structure (P, “1”) while the negative current will lead to the antiparallel structure (AP, “0”) according to STT theory.

We use a generalized Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation to describe the magnetization dynamics [39, 40],

$$\begin{aligned} \frac{d\mathbf{M}}{dt} = & -\gamma' \mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\alpha \gamma'}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) \\ & - \frac{2\mu_B J}{(1 + \alpha^2) e d M_s^3} g(\mathbf{M}, \mathbf{P}) \mathbf{M} \times (\mathbf{M} \times \mathbf{P}) \quad (1) \\ & + \frac{2\mu_B \alpha J}{(1 + \alpha^2) e d M_s^2} g(\mathbf{M}, \mathbf{P}) (\mathbf{M} \times \mathbf{P}), \end{aligned}$$

where the first term represents the precession torque and the second term represents the Gilbert damping torque. $\mathbf{H}_{\text{eff}}$ is the effective field, $\gamma' = \gamma/(1 + \alpha^2)$, γ is the electron gyromagnetic ratio, and α is the dimensionless damping parameter. The effective field includes the anisotropy field, the demagnetization field, the external field, the elastic field, and the exchange field; namely, $\mathbf{H}_{\text{eff}} = \mathbf{H}_k + \mathbf{H}_d + \mathbf{H}_{\text{ext}} + \mathbf{H}_{\text{elas}} + \mathbf{H}_{\text{ex}}$, given as

$$\mathbf{H}_{\text{eff}} = -\frac{1}{\mu_0} \frac{\delta E}{\delta \mathbf{M}}, \quad (2)$$

FIGURE 1: Schematic structure of CoFeB (2 nm)/MgO (2 nm)/CoFeB (16 nm) magnetic tunnel junction spin valve.

where E is the total energy, expressed by $E = E_k + E_d + E_{\text{ext}} + E_{\text{elas}} + E_{\text{ex}}$, where E_k , E_d , E_{ext} , E_{elas} , and E_{ex} are anisotropy energy (including magnetocrystalline and shape anisotropies) [41], demagnetization energy, Zeeman energy, elastic energy, and exchange energy, respectively. The details for obtaining E_k , E_d , E_{ext} , E_{ex} , and E_{elas} can be found in our previous papers [41–43]. The last two terms on the right side of (1) describe STT that tends to drag the magnetization away from its initial state to its final state. The scalar function is given by [39, 40], $g(\mathbf{M}, \mathbf{P}) = [-4 + (1 + \eta)^3 (3 + \mathbf{M} \cdot \mathbf{P}/M_s^2)]/4\eta^{3/2}]^{-1}$, where η is the spin polarization constant, $\mathbf{M}$ and $\mathbf{P}$ are the magnetization of free and fixed layers in Figure 1, and the angle between $\mathbf{M}$ and $\mathbf{P}$ is θ . $\mathbf{M} \cdot \mathbf{P}/M_s^2 = \cos\theta$. $\mathbf{H}_{\text{STT}}$ is the corresponding effective field given by $\mathbf{H}_{\text{STT}} = 2\mu_B J g(\mathbf{M}, \mathbf{P}) \mathbf{M} \times \mathbf{P}/(\gamma e d M_s^3)$, where μ_B , J , d , e , and M_s are the Bohr magneton, current density, thickness of the free layer, electron charge, and saturation magnetization, respectively.

The magnetic parameters employed in the simulations are as follows: saturation magnetization $M_s = 9.549 \times 10^5 \text{ A/m}$ [44, 45], Gilbert damping parameter $\alpha = 0.00439$ [46], spin polarization factor $\eta = 0.5$ [47], magnetic anisotropy constants $K_1 = 1.2 \times 10^4 \text{ J/m}^3$ and $K_2 = 0$ [37], elastic constants $c_{11} = 2.57 \times 10^{11} \text{ Nm}^{-2}$, $c_{12} = 1.62 \times 10^{11} \text{ Nm}^{-2}$, and $c_{44} = 1.05 \times 10^{11} \text{ Nm}^{-2}$ [37], and magnetostrictive constants $\lambda_{100} = 139 \text{ ppm}$ and $\lambda_{111} = 22 \text{ ppm}$ [44, 45]. We investigated the influence of normal substrate strains ε_{11} and ε_{22} on the magnetization state by assuming a zero shear strain. The dynamics of magnetization was investigated by numerically solving the time-dependent LLGS equation using the Gauss-Seidel projection method and the semi-implicit Fourier spectral method [48–53]. The samples were discretized in computational cells of $2 \times 2 \times 2 \text{ nm}^3$.

3. Results and Discussions

Figure 2 shows the hysteresis loops with the substrate misfit strains ($\varepsilon_{11} = \varepsilon_{22} = 0$ and 0.5%). Without the applied

FIGURE 2: Hysteresis loops of magnetization versus current density with strain and without strain.

strain, there is a square hysteresis loop of magnetization versus current density (M - J) curve. The critical current densities are 2.1×10^{11} A/m² from AP to P and -3.7×10^{11} A/m² from P to AP. At the biaxial strain 0.5%, we observe the decrease of critical current densities for magnetization switching (red hysteresis loop). The critical current densities are 1.3×10^{11} A/m² from AP to P and -2.7×10^{11} A/m² from P to AP. The positive substrate misfit strain reduces the critical current densities by pushing the magnetization from the out-of-plane to the in-plane directions. Therefore, the substrate misfit strain can be used effectively in assisting the STT induced magnetization switching.

Figure 3 shows the evolution of magnetization components $\langle m_z \rangle$ with different current densities and substrate misfit strains. For the black line, the magnetization is along the initial $-z$ -axis and keeps the AP structure without the applied current and strain. The red and pink lines represent the magnetization switching from AP to P and P to AP at the current densities of 1.0×10^{12} A/m² and -1.0×10^{12} A/m². Since the applied current densities are large enough to overcome the barrier, the magnetization will switch from AP to P or P to AP at the negative or positive current densities. We take the magnetization switching from AP to P, for example, to show the effect of misfit strain. If the biaxial positive strain $\epsilon_{11} = \epsilon_{22} = 0.5\%$ is applied, the magnetization switching (cyan line) is faster than that without strain (red line). However, the biaxial negative strain $\epsilon_{11} = \epsilon_{22} = -0.5\%$ will prolong the time of the magnetization switching (blue line). The mechanism of the phenomenon resulted from the fact that the positive strain will drag the magnetization along the in-plane direction, while the negative strain will push the magnetization back to the out-of-plane direction.

FIGURE 3: Time evolution of magnetization components $\langle m_z \rangle$ with different current densities and substrate misfit strains.

We can use the magnetic domain evolution to elucidate the effect of misfit strain. As shown in Figure 4, we show the corresponding magnetization distributions at the current density 1.0×10^{12} A/m² under different applied strains. Three rows correspond to the magnetization switching of red (zero strain), cyan (0.5%), and blue (-0.5%) lines in Figure 3. The colors represent different domain area: purple is $-z$, red is $+z$, and other colors are domain wall area. We observed that the magnetization was switched from the initial $-z$ -axis to the final $+z$ -axis due to the large current density input. This multidomain evolution process resulted from the large current input energy. In the first row, the initial magnetization was along $-z$ -axis. Without the strain, the magnetization switching process started from the outer to the inner of the free layer. However, the magnetization switching process started from the inner to the outer of the free layer in the negative strain. For the positive strain, we can observe that the nucleation starts from the center and diffuses to the edges.

4. Conclusions

In conclusion, we investigated the strain-assisted STT induced magnetization switching in CoFeB-based magnetic tunnel junctions by combining phase-field method with micromagnetic simulations. We proposed an effective method of using strain-assisted STT induced magnetization switching instead of using an external magnetic field. Since the tensile biaxial substrate misfit strains drag the magnetization into the in-plane directions, the critical current density and switching time are decreased significantly.

FIGURE 4: Magnetic domain evolutions with different misfit substrate strains during the magnetization switching.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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