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Micromagnetic simulation of critical current density of spin transfer torque switching in a full-Heusler $Co_2FeAl_{0.5}Si_{0.5}$ alloy spin valve nanopillar

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ABSTRACT

We investigated the critical current density of spin transfer torque switching in a full-Heusler $Co_2FeAl_{0.5}Si_{0.5}$ alloy spin-valve nanopillar through micromagnetic simulations. The simulations explain the experimental results on the resistance versus external magnetic field and yield good agreement with the measured switching behavior. It is shown that different magnitudes of current densities and directions of external magnetic fields give rise to a shift of resistance hysteretic loop and a variable range of switching. We demonstrated that three critical current densities have different slopes with Gilbert damping constant α and spin polarization constant η, indicating that α and η have different contributions to the critical current densities. Furthermore, we found that the area of resistance–current hysteretic loop decreases as the nanopillar size decreases. The domain structures indicated that the magnetization reversals have different switching processes between small and large sizes of pillars.

1. Introduction

In recent years, spin transfer torque (STT) switching, proposed by Slonczewski [1] and Berger [2] in 1996, has attracted considerable attention due to its application in high density magnetic random access memory (MRAM). STT devices offer superior performances such as large storage density, high switching speed, low energy consumption, and avoidance of cross writing. Spin polarized electrons carry spin angular momenta from the fixed layer to the free layer. It causes free layer switching when the current density exceeds a critical current density J_c. However, the critical current density required to induce the STT-based magnetization dynamics in the spin-valves is as high as 10^6–10^8 A/cm^2, and it is challenging to reduce J_c to achieve the compatibility with highly scaled complementary metal-oxide-semiconductor technology while maintaining the thermal stability.

The critical current density for spin transfer torque switching can be estimated by taking into account both spin pumping and the finite penetration depth of the transverse spin current [3–5]. In the macrospin approximation model, J_c at zero temperature can be described as

$$J_c = \frac{2e\alpha M_s t_F (H+H_k+2\pi M_s)}{\hbar\eta} \quad (1)$$

where α is the Gilbert damping constant, η is the spin polarization constant, M_s is the saturation magnetization, t_F is the thickness of the free layer, H is the external magnetic field, H_k is the magnetocrystalline anisotropy field, e is the elementary charge of an electron, and $\hbar$ is the reduced Planck constant. Many attempts have been made to reduce J_c, including using CoFeB as the free layer to reduce M_S; [6] with a double spin-filter structure, [7] an antiferromagnetic pinning structure, [8] or inserting a Ru spin scattering layer [9] to increase spin scattering, or using a composite free layer consisting of two ferromagnetic layers with various coupling types [10–13].

According to Eq. (1), Heusler alloys with lower M_s, smaller α and higher spin polarization factor η are excellent candidates for reducing J_c compared to CoFe, Fe, Co and Py. Experimental measurements of Aoshima et al. [14] showed that J_c of Co_2MnGe, Co_2FeSi, and $Co_{75}Fe_{25}$ spin-valves were 1.6×10^7, 2.7×10^7, and 5.1×10^7 J/cm^2, respectively. A large magnetoresistance ratio of 6.9% at room temperature (RT) for $Co_2FeAl_{0.5}Si_{0.5}$ (CFAS)/Ag/CFAS spin-valves was found.[15] Sukegawa et al.[16] first demonstrated efficient spin transfer switching in $Co_2FeAl_{0.5}Si_{0.5}$-based spin valve, and showed that the resistance–current curves exhibited a two-step switching process, originating from the interplay between the magnetocrystalline anisotropy of CFAS layers and STT. For both experiments and simulations of $Co_2FeAl_{0.5}Si_{0.5}$ spin valves under an appropriate negative current, there exists an intermediate (I) state with the direction of the magnetization perpendicular to their original antiparallel (AP) and final parallel (P) spin configurations, [16,17] i.e., the magnetization reversal from the initial AP state to

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the I state and then to the P state as the current decreases, forming a two-step switching in the negative part of the hysteretic loop. For a positive current, there is only one-step switching, i.e., the magnetization reversal from P to AP directly. However, there have been no discussions on what kind of conditions will affect the magnitude of the critical current density in the Heusler-based spin valve, such as the external magnetic field, size of nanopillar, spin polarization constant and Gilbert damping constant.

In this paper, we investigated the critical current density of spin transfer torque switching in a full-Heusler $Co_2FeAl_{0.5}Si_{0.5}$ alloy spin-valve nanopillar through micromagnetic simulations. In addition to the observation of the two-step switching behavior under an external magnetic field, we demonstrated the shifts in the resistance versus current hysteretic loop and the variable range of I state under the external magnetic fields. Furthermore, our investigation also shows that the critical current density increases with Gilbert damping constant α and decreases with spin polarization constant η, which can be used to evaluate different strategies for reducing J_c in experiments. We also present the R–J hysteretic loops and the corresponding domain evolution as a function of the nanopillar size with roughly the same aspect ratio, indicating different switching mechanisms for different sizes.

2. Model description

A spin valve device was investigated with the geometry similar to the structure of spin valve in Ref. 16[CFAS (20 nm)/Ag (4 nm)/CFAS (2.5 nm)]. As shown in Fig. 1, we employed a Cartesian coordinate system where the *x*-axis is the long axis of the ellipse along the CFAS [110] direction (easy axis) and the *y*-axis is along the short axis ([$\bar{1}$10]). The two CFAS layers are separated by a thin Ag layer, and the bottom CFAS layer is the free layer whose magnetization dynamics is triggered by a spin-polarized current. The top CFAS layer is the pinned layer with its magnetization vector P fixed in the direction along the positive *x* axis. The initial magnetization vector M of the layer is along the negative or positive *x* axis. The middle Ag layer is a space layer whose function is to avoid the exchange coupling between the two CFAS layers. The thickness of the spacer layer (4 nm) is much smaller than the spin diffusion length to conserve the spin momentum. The positive current is generally defined as electrons flowing from the free layer to the pinned layer.

The magnetization dynamics is described by using a generalized Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation, [1] which can be written as

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

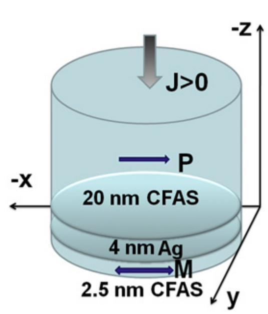

Fig. 1. Model geometry definition of CFAS (20 nm)/Ag (4 nm)/CFAS (2.5 nm) spin valve nanopillar in Cartesian coordinates.

where M is the magnetization of the free layer, P is the magnetization of the pinned layer, H_{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 and the exchange field, namely $H_{eff} = H_k + H_d + H_{ext} + H_{ex}$.

The last two terms on the right side of Eq. (2) describe STT that tends to drag the magnetization away from its initial state to its final state. The scalar function is given by [1]

$$g(M,P) = [-4 + (1+\eta)^3(3 + MP/M_s^2)/4\eta^{3/2}]^{-1} \quad (3)$$

where the angle between M and P is θ. $M \cdot P/M_s^2 = \cos\theta$.

H_{STT} is the corresponding effective field given by

$$H_{STT} = 2\mu_B J g(M,P) MP/(\gamma e d M_s^3) \quad (4)$$

where μ_B, J, d, i, M_s, are the Bohr magneton, current density, thickness of the free layer, electron charge, and saturation magnetization, respectively.

We adopted the following magnetic parameters [16], saturation magnetization $M_s = 9.0 \times 10^5$ A/m, exchange constant $A = 2.0 \times 10^{-11}$ J/m, and magnetocrystalline anisotropy constant $K_1 = -1.0 \times 10^4$ J/m^3. Other parameters are Gilbert damping parameter $\alpha = 0.01$, and spin polarization factor $\eta = 0.76$. The dynamics of magnetization was investigated by numerically solving the time-dependent LLGS equation using the Gauss–Seidel projection method [18,19] with a constant time step $\Delta t = 23.8993$ fs for getting the results exactly. The samples were discretized in computational cells of $2.5 \times 2.5 \times 2.5$ nm^3 [20–22].

3. Results and discussion

We investigated the critical current density of spin transfer torque switching in a full-Heusler $Co_2FeAl_{0.5}Si_{0.5}$ alloy spin-valve nanopillar with a device area of 250×190 nm^2. As shown in Fig. 2, the relative resistance versus external magnetic field (R–H) hysteretic loops were simulated with different positive current densities, and the external magnetic field is along the $+x$ or $-x$ axis. A two-step magnetization switching behavior, as observed experimentally [16] was obtained at a constant current density of 2.5×10^5 A/cm^2, and the curve yields good agreement with the experimental results. In the R–H curves, three states are evident: the parallel (P), antiparallel (AP), and intermediate (I: perpendicular to P) states. For one-step switching, the magnetization flips from P to AP are above the critical magnetic field. While for the two-step switching, the magnetization flip from AP to I first at a smaller magnetic field. Then, it switches from I to P at a larger field. We attributed this two-step switching to the fourfold in-plane

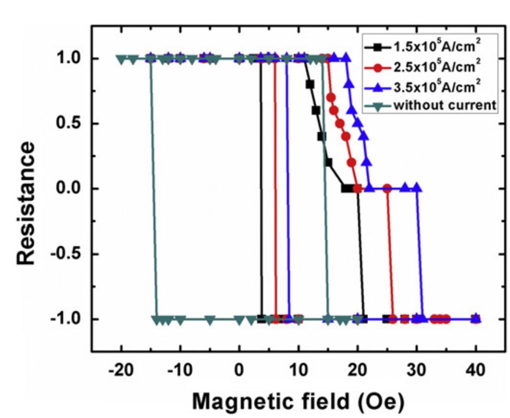

Fig. 2. Resistance versus external magnetic field (R–H) hysteretic loop at different current densities.