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Reduction of switching time in pentalayer nanopillar device with different biasing configurations

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ABSTRACT

The spin transfer torque assisted magnetization switching in a pentalayer nanopillar device is theoretically studied for different biasing configurations. The magnetization switching time is calculated for three different configurations (standard(no biasing), pinned layer biasing and free layer biasing), by numerically solving the governing dynamical Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation. The corresponding switching time for an applied current density of 3×10^{11} Am^{-2} is about 0.296 ns, 0.195 ns, and 0.108 ns respectively. Pinned layer biasing and free layer biasing increase the magnetization switching speed significantly. Reduction of switching time in the pinned layer biasing is due to the enhancement of spin transfer torque, whereas in the free layer biasing it is due to an additional magnetic torque which arises due to an applied magnetic field. The fastest magnetization switching is achieved for the free layer biasing configuration.

1. Introduction

Magnetization switching using the "Spin transfer torque" proposed by Slonczewski [1] and Berger [2], have recently attracted much interest due to its potential application in read/write heads [3], microwave frequency generators [4] and spin transfer torque random access memories (STTRAM) [5]. For STTRAM applications nanopillar must have small cell size ($4F^2$), fast access time (less than 10 ns), high endurance (10^{16}) and long retention time [6]. The basic element used in the STTRAM is a trilayer nanopillar which consists of two ferromagnetic layers separated by a non-magnetic metal layer. Out of the two ferromagnetic layers, first layer magnetization is fixed/pinned during the fabrication process with the help of anti-ferromagnet and it is called as pinned layer. The magnetization of another layer can be switched between two states either parallel or anti-parallel with respect to the pinned layer and it is called as free layer. Current passes through the pinned layer becomes spin polarized. The polarized current entered into the free layer via non-magnetic spacer layer produces a spin transfer torque due to the exchange interaction between the spins of conductive electrons and local magnetization [7]. As a response to spin transfer torque, the free layer magnetization begins to process, turning like a spinning-top about its easy axis. If the applied current is below a critical value, the magnetization relaxes back to its easy axis [8]. If the applied current is just above the critical, the magnetization follows many cycles of precession until its direction is reversed. When the applied current is well above the critical, the magnetization quickly reaches its reversed state [9]. The reduction of critical current density required to initiate the magnetization switching and increase the speed of magnetization switching are the important issues in STTRAM applications [10].

In order to increase the spin transfer torque efficiency and the switching speed, Fuchs et al. [11] introduced a pentalayer structure by adding a spacer and ferromagnetic pinned layer above the free layer in the trilayer structure based on the proposal from Berger [12], and showed that spin torque efficiency is increased in the case of pinned layers in the pentalayer structure are anti-aligned. The spin transfer torque efficiency enhancement in the pentalayer nanopillar reduces the critical current density very much [13]. In 2007, Devolder et al [14] introduced a biasing in the trilayer structure and comparing the benefits of pinned layer and free layer biasing, and showed that magnetization switching speed is enhanced by biasing. Based on the above two studies, in the present work, we study the spin transfer torque switching in pentalayer nanopillar structure (pinned 1/spacer 1/free/spacer 2/pinned 2) for various biasing configurations. In the pentalayer nanopillar, second pinned layer magnetization is aligned anti-parallel to the first pinned layer magnetization and free layer magnetization is

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initially aligned along its easy axis. First, we investigate the magnetization switching dynamics of the free layer for the above said configuration called as standard configuration(SC). Then, we study the switching process for pinned layer biasing and free layer biasing configurations. In the pinned layer biasing, either the magnetization of the first pinned layer or second pinned layer magnetization can be tilted with respect to the free layer easy axis. In the free layer biasing, the magnetization of the free layer is pulled away from the easy axis by an external magnetic field. Magnetization switching dynamics of the free layer is governed by the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation and it is studied by numerically solving the LLGS equation.

The paper is organized as follows. In Section 2, description about the geometry of pentalayer nanopillar device and the construction of dynamical equation for magnetization switching process by LLGS equation are presented. Numerical studies of standard, pinned layer biasing and free layer biasing configurations and their results are discussed in Section 3. Finally, concluding remarks are made in Section 4.

2. Model and dynamical equation

The pentalayer nanopillar device considered for our study has three ferromagnetic layers (two pinned layers and one free layer) and two non-magnetic metal layers (spacer layers). A schematic diagram of the above device is shown in the Fig. 1. In the figure, the first pinned layer magnetization is aligned along the easy axis and second pinned layer magnetization is anti-aligned with respect to the first one and their magnetizations are fixed. In order to analyze the magnetoresistance behavior and read the magnetization status of the free layer, two different thickness of pinned layers (first (bottom) pinned layer with larger thickness than that of second (top) pinned layer) have been chosen and the procedure to read the magnetization status from the magnetoresistance study is discussed in detail elsewhere [15]. The free layer is sandwiched between two non-magnetic spacer layers. Magnetization of the free layer is free to move and it has in-plane magnetic anisotropy. The applied current is normal to the plane of device (along z-direction), and it becomes spin polarized while passing through the first pinned layer. The spin polarized current transferred through non-magnetic metal layer, produces a torque in free layer due to the change in the electron spin angular momentum and it switches the magnetization of the free layer. The non-participant and scattered electrons from the free layer is entered into the second pinned layer, but since its magnetization is in anti-parallel direction, i.e. in high resistance configuration, the electrons are reflected back into the free layer and it produces an additional spin torque in the free layer [16]. This additional torque reduces the critical current density and also enhances the magnetization switching speed of the free layer. The magnetization switching process of the free layer in the pentalayer nanopillar device is governed by the LLGS equation and it can be written in dimensionless form as [17,18],

$$\frac{d\mathbf{m}}{d\tau} = -[\mathbf{m}\times\mathbf{h}_{\mathbf{eff}}] - \alpha[\mathbf{m}\times(\mathbf{m}\times\mathbf{h}_{\mathbf{eff}})] + a_j[\mathbf{m}\times(\mathbf{m}\times\mathbf{m}_{p1})] - a_j[\mathbf{m}\times(\mathbf{m}\times\mathbf{m}_{p2})]. \quad (1)$$

$$\mathbf{m} = (m^x, m^y, m^z), \quad \mathbf{m}^2 = m^{x2} + m^{y2} + m^{z2} = 1. \quad (2)$$

where α is the Gilbert damping parameter, $a_j = \frac{pJ\hbar}{\mu_0 edM_s^2}$ is the spin transfer torque coefficient and its value is, positive when electrons flow from pinned layer to free layer and negative when electrons transfer from free layer to pinned layer [19]. p is the polarization factor, J is the current density applied from the source, $\hbar$ is the reduced Planck's constant, μ_0 is the permeability of free space, e is the charge of an electron, d is the thickness of the free layer and M_s is the saturation magnetization of the free layer. $\mathbf{m}_{p1}$ and $\mathbf{m}_{p2}$ are unit magnetization vectors in first and second pinned layer respectively. To account the non-collinearity between the free layer easy axis and pinned layer magnetization, we shall write pinned layers magnetization as $\mathbf{m}_{p1} = \cos\theta_1\mathbf{e}^x + \sin\theta_1\mathbf{e}^y$ and $\mathbf{m}_{p2} = \cos(\pi+\theta_2)\mathbf{e}^x + \sin(\pi+\theta_2)\mathbf{e}^y$. Where θ_1 and θ_2 are the angle between the free layer easy axis and magnetization of the first and second pinned layer respectively. $\mathbf{m} = \frac{\mathbf{M}}{M_s}$ is the dimensionless magnetization of the free layer, and $\tau = \gamma M_s t$ is the dimensionless time, where γ is the gyromagnetic ratio of free electron. $\mathbf{h}_{eff}$ is the effective field acting on the free layer and it can be written as,

$$\mathbf{h}_{eff} = \mathbf{h}_{ma} + \mathbf{h}_{shape} + \mathbf{h}_{ext}, \quad (3)$$

where $\mathbf{h}_{ma}$ is the field contribution due to the magneto-crystalline anisotropy. Since the free layer has in-plane magneto-crystalline anisotropy along its easy axis (x-direction), the corresponding field can be written as $\mathbf{h}_{ma} = h_a m^x \mathbf{e}^x$. $\mathbf{h}_{shape}$ is the term for the shape anisotropy caused by the demagnetizing field and it can be written as $\mathbf{h}_{shape} = -(N_x m^x\mathbf{e}^x + N_y m^y\mathbf{e}^y + N_z m^z\mathbf{e}^z)$. Since the free layer is in the xy-plane, $N_x = N_y = 0$ and N_z=1. Therefore, the field due to shape anisotropy becomes, $\mathbf{h}_{shape} = -m^z\mathbf{e}^z$. $\mathbf{h}_{ext}$ is the field contribution from the external applied field and it is applied

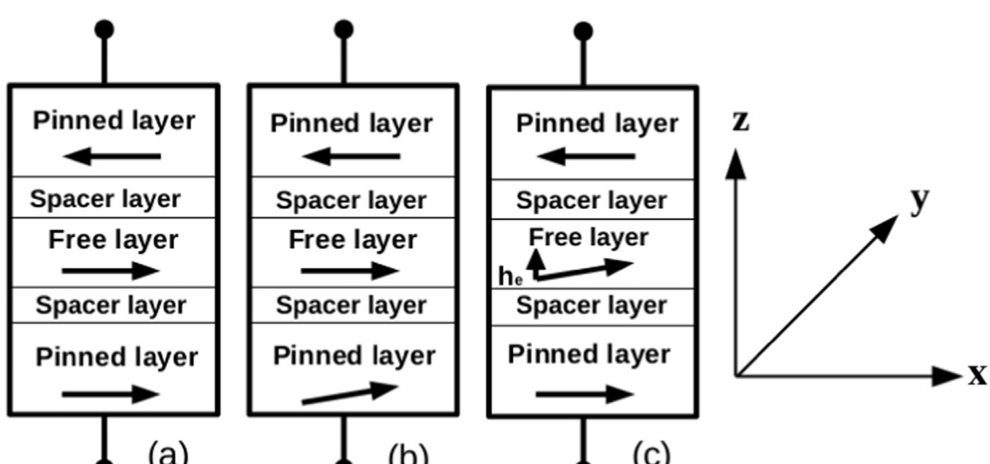

Fig. 1. Schematic sketch of the pentalayer nanopillar device. (a) Standard configuration (b) pinned layer biasing configuration (c) Free layer biasing configuration.