Switching magnetic junction by joint action of current pulse and magnetic field: Numerical simulation

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Abstract

The results are presented of a numerical simulation of the switching magnetic junction by a spin-polarized current pulse under applied magnetic field with the current density and field below the threshold values. A possibility is shown of the switching with controllable delay relative to the current pulse.

The switching magnetic junction by spin-polarized current [1] attracts continuous attention both of experimentalists and theorists. This is due to a possible practical application of the effect for high-density recording information by current in magnetic media, as well as interesting problems related with the attempts of theoretical interpretation of the experimental results and prediction new effects.

There are two important problems in experimental investigation and application of the effect, namely, lowering the switching threshold and shortening the current pulses causing the switching. Solution of the problems will allow decreasing the Joule heating of the junction layers and avoiding destruction of the switching elements by the flowing current.

Nowadays several ways have been proposed to lower the threshold current density, under which the initial configuration becomes unstable and switches to another one with different electric resistance. These are proper choice of the barrier layer material [2], using diluted magnetic semiconductors as the pinned and free layers of the magnetic junctions [3], using combination of the layer parameters corresponding to efficient spin injection from the pinned layer to the free one and “locking up” the injection at the interface between the free layer and the nonmagnetic layer closing the electric circuit [4], using a noncollinear initial configuration of the magnetic junction [5, 6, 7, 8].

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In Ref. [9] attention was paid to a possibility of substantial lowering of the current density needed to switch a magnetic junction under joint action of the current and magnetic field with the current density and field below the corresponding threshold values when the factors mentioned act singly. If the magnetic field strength is close enough to the threshold value (the anisotropy field), but slightly smaller than it, then a current with density below substantially than the threshold value without magnetic field can help to switching. Note, that the presence of the magnetic field does not break local character of the exchange switching the magnetic junction, because the magnetic field of such a value cannot do switching alone (without current).

Together with the lowering current density of the stationary current, the presence of the magnetic field opens possibility of switching by short current pulses. Varying the pulse amplitude and duration allows switching with a time delay relative to the current pulse.

Theoretical investigation of the switching by short current pulses is related with solving a set of nonlinear differential equations (the Landau–Lifshitz equations) with variable coefficients. Because of difficulty of this task, it is need to use numerical solution.

Let us consider a magnetic junction with the free layer thickness small compared to the spin diffusion length, so that the macrospin approximation [9] is applicable. The high spin injection conditions [4] are assumed to be valid, so that the switching magnetic junction is determined by creating nonequilibrium spin polarization with injected spins [10, 11]. Under these approximations, the free layer magnetization in presence of the time-depended current $j(t)$ perpendicular to the layers is described by the following equation [9]:

$$\frac{d\hat{M}}{dt} - \kappa \left[ \hat{M}, \frac{d\hat{M}}{dt} \right] + \gamma \left[ \hat{M}, \mathbf{H} \right] + \gamma H_a \left( \hat{M} \mathbf{n} \right) \left[ \hat{M}, \mathbf{n} \right] + \gamma H_a \left( j(t) \right) \left[ \hat{M}, \hat{M}_1 \right] = 0. \tag{1}$$

Here $\hat{M} = M/|M|$ is the unit vector along the free layer magnetization vector $\mathbf{M}$, $\mathbf{H}$ is the external magnetic field, $\mathbf{H}_d$ is the demagnetization field, $H_a$ is the anisotropy field, $\mathbf{n}$ is the unit vector along the anisotropy field, $\mathbf{M}_1$ is the unit vector along the pinned layer magnetization, $\kappa$ is the Gilbert damping constant, $\gamma$ is the gyromagnetic ratio; $j_0 = \frac{eH_aL}{\mu_B \alpha \tau Q_1}$ has the meaning of the threshold current density for the switching magnetic junction by a stationary current (an infinitely long pulse) without magnetic field; $\mu_B$ is the Bohr magneton, $\alpha$ is the $sd$ exchange interaction constant, $\tau$ is the electron spin relaxation time, $L$ is the free layer thickness, $Q_1$ is the spin polarization of the pinned (injecting) layer conduction.

The last term in the left-hand side of Eq. (1) describes effect of the spin-polarized current on the magnetic lattice under high spin injection.
Let us consider a configuration with $H = \{0, 0, H\}$, $n = \{0, 0, 1\}$, $H_d = -4\pi M\{M_z, 0, 0\}$, $M_1 = \{0, 0, 1\}$; $x$ axis being directed along the current, $yz$ plane being coincided with the layer plane. On the spherical coordinates $(\theta, \phi)$ with the polar axis along $z$ axis the vector equation (1) determining direction of the free layer magnetization vector $\hat{M} = \{\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta\}$ takes the form of the following set of equations:

$$\frac{d\theta}{dT} = \frac{\sin \theta}{1 + \kappa^2} \left\{ -\kappa A(\theta, \phi, t) + B(\phi) \right\}, \quad (3)$$

$$\frac{d\phi}{dT} = \frac{1}{1 + \kappa^2} \left\{ A(\theta, \phi, t) + \kappa B(\phi) \right\}, \quad (4)$$

where

$$A(\theta, \phi, t) = h + h_a \cos \theta + \cos \theta \cos^2 \phi + h_a \frac{j(t)}{j_0}, \quad (5)$$

$$B(\phi) = \cos \phi \sin \phi, \quad (6)$$

$$h = \frac{H}{4\pi M}, \quad h_a = \frac{H_a}{4\pi M}, \quad T = 4\pi \gamma Mt.$$  

A numerical solution of Eqs. (3), (4) was found using Simulink software in the MATLAB system [13].

The following parameter values were given: $\kappa = 0.03$, $h_a = 0.01$. The initial relative orientation of the pinned and free layers was assumed to be antiparallel ($\theta = \pi$). At high enough current density and/or magnetic field such a configuration becomes unstable, however, an initial deviation is needed which is promoted by thermal fluctuations in reality. The presence of the thermal noise creating deviation of the free layer magnetization from the initial unstable stationary equilibrium state was imitated with giving a small initial deviation from such a state by angle of 0.01 radians in the layer plane where the demagnetization field does not prevent fluctuation deviation, so that minimal fluctuation energy is needed. The time dependence of the spin polarized current density $j(t)$ was given as a rectangular pulse of $w$ duration. The chosen values of the magnetic field and the pulse amplitude, $H = 0.9H_a$ and $j = 0.9j_0$, respectively, being 90% of the corresponding threshold values, avoid possibility of switching the junction by the field or by the current singly. Therefore, the switching describing by the solution to be found is caused by joint action of the current and magnetic field.

The simulation results are presented below as a time dependence of the free layer deviation angle from the initial antiparallel orientation. The dimensionless time is laid off as abscissa with $t_0 = (1 + \kappa^2)/(4\pi \gamma M)$ as the time unit; at $M = 900$ G one nanosecond corresponds to 200 scale divisions of the abscissa ($t_0 = 0.005$ ns). The step shows the current turning on and turning off instants of time.

There is a minimal pulse duration under which the switching can occur yet with the given values of the magnetic field and the pulse amplitude. In Fig. 1 the free layer deviation angle from the initial antiparallel orientation
Figure 1: Time dependence of the deviation angle of the free layer magnetization vector from the initial antiparallel orientation under the switching with joint action of the current pulse and the magnetic field. $j/j_0 = 0.9$, $H/H_a = 0.9$, $w = 67.15t_0$. 
Figure 2: Time dependence of the deviation angle of the free layer magnetization vector from the initial antiparallel orientation with the pulse duration below the threshold value. $j/j_0 = 0.9$, $H/H_a = 0.9$, $w = 67.14t_0$.

is shown as a function of time at $w = 67.15t_0$. It is seen that the switching takes place with substantial time delay relative to the pulse. At the given values of the magnetic field and the current pulse amplitude, that $w$ value is threshold one: with decreasing the pulse duration only by 0.01$t_0$ the switching does not occur (Fig. 2). Under increasing in the pulse duration the switching delay time decreases (Fig. 3).

Lengthening the pulse makes it possible switching with lower values of the magnetic field and/or the current density. In the limiting case of the pulse duration much longer than the precession period, the switching condition takes the form corresponding to the stationary current $[14]$, 

$$\frac{H}{H_a} + \frac{j}{j_0} > 1.$$  \hfill (7)

It is seen from Fig. 1 that the switching occurs as two stages, and the longer stage is realized after the current turns off. This fact may be explained by the following way. If the initial position of the magnetization vector is not exactly parallel to the external magnetic field, but is deviated from the antiparallel direction by some angle $\psi$, then the magnetic field $H > H_a \cos \psi$ is needed for the switching, the lower, the greater the deviation. The role of the current pulse is that it, acting together with the magnetic field, deviates the magnetization vector from the antiparallel direction by an angle large enough that the magnetic field could do the junction switching alone.
Figure 3: Decreasing (cf. Fig. 1) time delay of the switching under pulse lengthening. $j/j_0 = 0.9$, $H/H_a = 0.9$, $w = 75t_0$.

The results show possibility of the switching magnetic junctions by joint action of the magnetic field and current pulse. Varying the pulse amplitude and duration allows obtaining, if necessary, a delayed switching with controllable delay time.

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