Precession frequency and switching time of the magnetization vector of the spin-valve free layer with longitudinal anisotropy

Iuliia A Iusipova
IPPM RAS, Department of design of microelectronic components for nanotechnology, 124365, Moscow, Russia
E-mail: linda_nike@mail.ru

Abstract. In this paper, a magnetization vector dynamics of a spin-valve free layer with the planar anisotropy based on various materials was simulated. Two dynamics types were identified, being of practical interest for MRAM (switching) and STNO (stable precession). The range of current and field values, corresponding to these spin-valve operation modes, were obtained. The numerical calculations of the switching time shown that Co$_{80}$Gd$_{20}$ is the best material for a spin valve as a part of MRAM. As a result of calculating the precession frequency, it was concluded that the most suitable for fabrication of STNO ferromagnetic layers is the alloy Fe$_{60}$Co$_{20}$B$_{20}$.

1. Introduction
In the classical theory, the magnetic states of ferromagnets are controlled by an applied magnetic field. In 1996, J. Slonchevsky [1] predicted another way to change the magnetic configuration of ferromagnetic thin films using a spin-polarized current. The angular momentum transferred by the spin-polarized current transmits the torque to the magnetization vector, which leads to its switching or constant precession. A change of the magnetization vector projection onto the anisotropy axis causes a magnetoresistance variation of the structure, which entails voltage fluctuations in the external circuit. Magnetization switching is the main mode of the magnetoresistive random access memory (MRAM) operation [2, 3], and the magnetization vector precession is used in the work of spin-transfer nano-oscillators (STNO) [4].
The simplest configuration of the MRAM cell and the spin-transfer oscillator consists of a relatively thick “pinned” ferromagnetic layer, which serves as a current polarizer, a non-magnetic layer, and a relatively thin “free” layer. An antiferromagnetic layer is needed to fix the magnetization of the pinned layer (figure 1). A non-magnetic metal (for example, copper, platinum) or a thin dielectric (for example, MgO) is used as a nonmagnetic interlayer. The similar structure is usually called a spin valve or magnetic tunnel junction (MTJ), respectively.

The main objective of this work is to calculate the switching time and oscillation frequency of the spin valve placed in the magnetic fields of various directions, as well as the selection of the most suitable ferromagnetic materials and magnetic field configurations, which provide the best switching and frequency characteristics for MRAM and STNO, respectively.

2. Basic equations

The object of this study is a spin valve with planar anisotropy of the layers. The side of the valve square cross section was equal a = 11 nm. The anisotropy axis was directed along one of the sides of the square. The free layer thickness was \( d_1 = 2 \) nm, the pinned layer thickness was \( d_2 = 5 \) nm, and the thickness of the copper nonmagnetic interlayer was \( d_N = 1.2 \) nm. The axis \( OX \) of the coordinate system associated with the structure was directed along the anisotropy axis. The structure was placed in a magnetic field \( \mathbf{H} \), which can be directed along one of the coordinate system axes. \( H_X, H_Y, H_Z \) are the projection of the vector \( \mathbf{H} \) on the corresponding axis. An electric current of density \( J \) is passed perpendicular to the plane of the layers. \( \mathbf{M} \) is the magnetization vector of the spin-valve free layer, and \( \mathbf{s} \) is the unit vector that coincides with the direction of the pinned layer magnetization (figure 1).

For the ferromagnetic layers, such materials as cobalt Co and iron Fe (single-crystal films which are easier and cheaper to obtain), alloys \( \text{Fe}_{60}\text{Co}_{20}\text{B}_{20} \) and \( \text{Fe}_{70}\text{Co}_{30} \) (they have a high spin polarization parameter \( P > 0.5 \)), and alloys \( \text{Co}_{93}\text{Gd}_{7} \) and \( \text{Co}_{80}\text{Gd}_{20} \) (they have the best magnetic properties to reduce the switching magnetic field) are considered. In [5], the magnetic parameters of these materials are presented in more detail. Defects in the microstructure of materials are not taken into account in our model.

The magnetization vector dynamics of the spin-valve free layer \( \mathbf{M} \) is described by the Landau-Lifshits-Gilbert equation

\[
\frac{\partial \mathbf{M}}{\partial t} = -\gamma |\mu_0| [\mathbf{M} \times \mathbf{H}_{\text{eff}}] + \frac{\alpha}{M_s} \left[ \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right],
\]

where \( \gamma \) is the gyromagnetic ratio, \( \alpha \) is the dimensionless dissipation coefficient, \( M_s \) is the saturation magnetization.

The effective magnetic field \( \mathbf{H}_{\text{eff}} \) is included the magnetic anisotropy field, the demagnetization field, the effective field created by the spin-polarized injection current, and the external magnetic field. The details of the bifurcation analysis of the dynamic system (1) were given in [2, 5, 6].

The projection variation of the magnetization vector \( \mathbf{M} \) on the \( OX \) anisotropy axis due to the giant magnetoresistance effect leads to the change in the output signal \( U \) [7]. Its value is determined by the following expression:

\[
U = J\alpha^2 \left( \frac{R_P + R_{AP}}{2} + \frac{R_P - R_{AP}}{2} \frac{M_X}{M_s} \right),
\]

where \( M_X \) is the vector \( \mathbf{M} \) projection on the axis \( OX \), \( R_P \) and \( R_{AP} \) is the resistance of the spin valve in the parallel and anti-parallel states (table 1), respectively. According to the resistor model of the giant magnetoresistance for the structure of the selected geometry, “the current perpendicular to plane”, the equations for the resistances \( R_P \) and \( R_{AP} \) can be represented as [8]
\[ R_p = \frac{((d_1 + d_2) \rho_{up} + d_N \rho_N)((d_1 + d_2) \rho_{down} + d_N \rho_N)}{a^2((d_1 + d_2) \rho_{up} + 2d_N \rho_N + (d_1 + d_2) \rho_{down})}, \]
\[ R_{AP} = \frac{(d_1 + d_2) \rho_{up} + 2d_N \rho_N + (d_1 + d_2) \rho_{down}}{4a^2}, \]

where \( \rho_{up, down} = \frac{\rho}{1 \pm F} \), \( \rho \) is ferromagnetic layers resistivity (table 1), \( \rho_N \) is nonmagnetic interlayer resistivity (for copper \( \rho_N = 1.67 \times 10^{-8} \Omega \cdot m \) [9]).

### Table 1. Spin valve parameters for different materials of ferromagnetic layers.

| Material          | \( P \)  |
|-------------------|----------|
| Co (cobalt)       | 0.35 [5] |
| Fe (iron)         | 0.40 [5] |
| Fe\(_{70}\)Co\(_{30}\) | 0.55 [5] |
| Fe\(_{60}\)Co\(_{20}\)B\(_{20}\) | 0.52 [10] |
| Co\(_{93}\)Gd\(_{7}\)  | 0.30 [5] |
| Co\(_{80}\)Gd\(_{20}\) | 0.1 [5]  |

For more detailed description of the calculation methodology of the two-component alloys resistivity see [11]. However, for the practical applications, the films resistivity must be measured experimentally.

3. Magnetization vector dynamics

The dynamics of the vector \( \mathbf{M} \) was calculated by the Runge–Kutta method. The perturbation regarding the equilibrium position was taken 0.0001.

The switching mode and the stable precession mode are the main types of dynamics that are of practical importance for MRAM and STNO. From the point of view of the qualitative theory of dynamical systems, the precession mode represents a limit cycle.

3.1. Magnetization Vector Switching

The process of the logical "1" writing in the MRAM cell corresponds to the change of the direction of the magnetization vector \( \mathbf{M} \) in the free layer to the antiparallel direction of the pinned-layer magnetization vector \( \mathbf{s} \). The parallel direction of the vector \( \mathbf{M} \) corresponds to the equilibrium point \( T_1 \), and the antiparallel direction — to the equilibrium position \( T_2 \). Switching of the spin valve occurs when exposed to current, the magnetic field, or the combination of both. We agree that the logical "1" writing corresponds to the direction of the current opposite to the axis \( OZ \). Then, the logical "0" recording corresponds to the direction of current along the \( OZ \) axis. Similarly, to switch the vector \( \mathbf{M} \) from point \( T_1 \) to point \( T_2 \), it is necessary to apply the magnetic field antiparallel to the axis \( OX \), and to switch from the equilibrium position \( T_2 \) to the position \( T_1 \) — parallel to the axis \( OX \) (figure 1).

Figure 2a demonstrates switching from the point \( T_1 \) to the point \( T_2 \) of the free-layer magnetization vector of the \( \text{Co}_{80}\text{Gd}_{20} \)-based spin valve when \( H = 0 \) and \( J = 2.41 \times 10^6 \text{ A/cm}^2 \). Figure 2b shows the corresponding volt-second characteristic obtained by formula (2). The switching time \( t_{1-2} \) of the spin valve, in this case, will be equal to 184 ns.

In figure 3a the numerical calculation result of the reciprocal of the recording time \( t_{1-2} \) versus current density \( J \) for various materials were shown.
Figure 2. The switching of the free-layer magnetization vector of the Co$_{80}$Gd$_{20}$-based spin valve (a); the time dependence of the output voltage at the same parameters (b).

The dependence $t_{1-2}^{-1}(J)$ has the linear character. The functions of switching time $t_{2-1}$ of the vector $\mathbf{M}$ from position $T_2$ to position $T_1$ versus magnetic field $H_X$ parallel to the axis $OX$ ($J = 0$, $H_Y = 0$, $H_Z = 0$) were shown in figure 3b. The maximum point of the function $t_{2-1}(H_X)$ corresponds to the moment of changing the singular point $T_2$ type from a saddle to an unstable focus.

The dependences $t_{1-2}^{-1}(J)$ and $t_{2-1}(H_X)$ were numerically calculated by modeling the dynamics of the vector $\mathbf{M}$ by the Runge-Kutta method and the subsequent analysis of the resulting hodographs.

Figure 3. The dependences switching time $t_{1-2}$ on the current density $J$ (a); the dependences switching time $t_{2-1}$ versus field $H_X$ (b).

The Co$_{80}$Gd$_{20}$-based spin valve has the lowest critical switching current $J_{\text{min}} = 1.56 \cdot 10^6$ A/cm$^2$, and the Fe$_{60}$Co$_{20}$B$_{20}$-based spin valve has the highest value $J_{\text{min}} = 1.25 \cdot 10^8$ A/cm$^2$. The switching time of the Co$_{80}$Gd$_{20}$-based spin valve at the current close to $J_{\text{min}}$ was 960 ns, however, with an increase in current, it significantly decreases. With the current $J = 1.25 \cdot 10^8$ A/cm$^2$, the switching

Figure 4. The dynamics of the free-layer magnetization vector of the Co$_{80}$Gd$_{20}$-based spin valve in magnetic field parallel to the axis $OX$ (a); the volt-second characteristic at the same parameters (b).
time for Co_{80}Gd_{20} is only 1.8 ns, which is 9 times less than the switching time for Fe_{60}Co_{20}B_{20} with the same current.

The smallest critical switching magnetic field $H_{\text{min}} = 3.13 \cdot 10^3$ A/m has the spin valve with the ferromagnetic layers made of Co_{93}Gd_{7}. The shortest switching time $t_{2-1}$, which is equal to 2–4 ns, shown the Fe_{60}Co_{20}B_{20}-based spin valve. The switching time $t_{2-1}$ for Co_{93}Gd_{7} is always 3–5 times longer than for Fe_{60}Co_{20}B_{20}, at the equal values of the magnetic field.

3.2. Magnetization Vector Precession
For STNO, the regimes with precession, in which the magnetization vector projection on the anisotropy axis varies periodically, are important. This leads to a periodic significant change in the output signal $U$.

In figure 4a, the vector magnetization $\mathbf{M}$ dynamics for the Co_{80}Gd_{20}-based spin valve in the magnetic field parallel to the axis $OX$ ($H_X = 1.6 \cdot 10^4$ A/m, $H_Y = 0$, $H_Z = 0$) is shown. In this case, the value of the current density is $J = 1.67 \cdot 10^7$ A/cm$^2$, with the oscillation frequency being 0.18 GHz and the amplitude of oscillations $U_{\text{max}} = 0.17$ $\mu$V. The pairs of trajectories that came out of the points $T_1$, $T_3$, and $T_4$, $T_5$ and $T_6$ are symmetric about the axis $OX$ (figure 4a), therefore, they have the same volt-second characteristics (figure 4b). Around the unstable foci $T_3$ and $T_4$, there are two symmetric about the axis $OX$ stable limit cycles. The point $T_2$ is the stable focus, so, in this case, there are three possible outcomes of the magnetization vector dynamics: winding on one of the two limit cycles or switching to the point $T_2$.

Figure 5. The stable precession of the vector $\mathbf{M}$ of the Fe_{60}Co_{20}B_{20}-based spin valve in magnetic field parallel to the axis $OY$ (a); the time dependence of the output signal at the same parameters (b).

Figure 6. The stable precession of the free-layer magnetization vector of the cobalt-based spin valve in magnetic field parallel to the axis $OZ$ (a); the volt-second characteristic at the same parameters (b).
The time for establishing oscillations $\tau$ depends on the real part of the eigenvalues $\Re f$ of the linearization matrix for the trajectory at the start point. Under these conditions, points $T_3$ and $T_4$ have the minimum $\Re f = 0.03$, therefore, the trajectories leaving these points are characterized by the maximum time for establishing oscillations $\tau_{\text{max}} = 97 \text{ ns}$.

Figure 5a presents the stable precession for the layered structure with ferromagnetic layers made of $\text{Fe}_{60}\text{Co}_{20}\text{B}_{20}$, which is placed in the magnetic field parallel to the axis $OY$ ($H_X = 0, H_Y = -5 \cdot 10^5 \text{ A/m}, \ H_Z = 0$). The value of the current density $J$ is $3.7 \cdot 10^8 \text{ A/cm}^2$.

**Table 2.** Current density and magnetic field intervals, for which limit cycles are appeared, frequencies $v$ and amplitudes of output signal oscillations $U_{\text{max}}$ for various materials.

| Material        | Field direction | $H$, $\cdot 10^6 \text{ A/m}$ | $J$, $\cdot 10^8 \text{ A/cm}^2$ | $v$, GHz | $U_{\text{max}}$, $\mu\text{V}$ |
|-----------------|----------------|-------------------------------|---------------------------------|---------|-------------------------------|
| $\text{Co(coiblt)}$ | $OX$           | 0.42–0.98                     | 2.24–12.72                     | 2.1–8.0 | 4.83–54.39                    |
|                 | $OY$           | 0.56–2.80                     | 2.34–35.16                     | 2.0–17.0| 5.29–499.60                   |
|                 | $OZ$           | 1.07–2.80                     | 1.17–35.16                     | 2.4–17.6| 6.58–506.31                   |
|                 | $OX$           | 0.07–0.79                     | 1.21–14.51                     | 1.8–9.8 | 8.67–178.84                   |
| $\text{Fe(iron)}$ | $OY$           | 1.25–1.88                     | 1.86–42.79                     | 1.3–14.3| 8.29–1280.20                  |
|                 | $OZ$           | 0.50–1.88                     | 1.86–37.21                     | 1.4–9.5 | 55.5–1170.00                  |
|                 | $OX$           | 0.08–1.15                     | 0.70–8.35                      | 2.0–8.4 | 15.28–184.12                  |
| $\text{Fe}_{70}\text{Co}_{30}$ | $OY$           | 0.14–2.10                     | 1.39–27.81                     | 1.4–15.1| 9.41–1666.80                  |
|                 | $OZ$           | 0.42–2.10                     | 1.39–25.04                     | 1.16–10.4| 77.96–1549.20                |
|                 | $OX$           | 0.47–1.01                     | 2.32–6.03                      | 1.7–6.4 | 44.19–247.02                  |
| $\text{Fe}_{60}\text{Co}_{20}\text{B}_{20}$ | $OY$           | 0.25–1.87                     | 1.86–22.26                     | 1.2–13.2| 54.29–2756.60                 |
|                 | $OZ$           | 0.64–1.87                     | 0.93–19.48                     | 1.4–7.8 | 72.55–2546.90                 |
|                 | $OX$           | 0.02–0.52                     | 0.35–7.78                      | 0.6–4.6 | 1.56–39.84                    |
| $\text{Co}_{92}\text{Gd}_{7}$ | $OY$           | 0.07–1.06                     | 1.41–21.21                     | 0.3–7.9 | 1.60–256.60                   |
|                 | $OZ$           | 1.4–1.06                      | 0.71–19.10                     | 0.1–4.79| 6.35–248.30                   |
|                 | $OX$           | 0.02–0.05                     | 0.02–0.28                      | 0.1–0.6 | 0.01–0.17                     |
| $\text{Co}_{80}\text{Gd}_{20}$ | $OY$           | 0.03–0.12                     | 0.05–0.51                      | 0.02–0.76| 0.02–0.93                    |
|                 | $OZ$           | 0.08–0.12                     | 0.02–0.51                      | 0.08–0.46| 0.01–0.97                     |

The time dependence of the output signal $U$ (figure 5b) shows that the trajectory of the tip of $\mathbf{M}$ that leaves the point $T_6$ has the maximum establishing time of oscillations $\tau_{\text{max}} = 2.2 \text{ ns}$. The frequency of oscillations $v$, in this case, is $4.4 \text{ GHz}$, and the amplitude of oscillation is $U_{\text{max}} = 0.4 \text{ mV}$.

The magnetization vector dynamics $\mathbf{M}$ for the cobalt-based spin valve in a magnetic field parallel to the axis $OZ$ ($H_X = 0, H_Y = 0, H_Z = 1.9 \cdot 10^6 \text{ A/m}$) at the current $J = 1.0 \cdot 10^9 \text{ A/cm}^2$ was shown in figure 6a. In figure 6b, the corresponding volt-second characteristic are presented. In this case, the frequency and amplitude of oscillations are $7.5 \text{ GHz}$ and $0.15 \text{ mV}$, respectively. The maximum time for establishing oscillations $\tau_{\text{max}}$ is typical for the trajectory that leaves the point $T_6$; it is equal $2.1 \text{ ns}$.

It should be noted that, in the case, when the magnetic field is parallel to the axis $OY$ or $OZ$, the trajectory of the magnetization vector wound on the limit cycle around the axis, along which the magnetic field is directed (figure 5a, figure 6a), and the volt-second characteristics approach to harmonic one (figure 5b, figure 6b). At the same time, if the field is directed along the axis $OX$, two
symmetrical about this axis limit cycles are appeared (figure 4a), and the type of dependence $U(t)$ is close to saw-tooth one (figure 4b).

From the table 2, it follows that Fe$_{60}$Co$_{20}$B$_{20}$ -based spin valve has the maximum amplitude of oscillations $U_{\text{max}}$, when placed in the magnetic field, directed along the axis $OY$. The spin valve with ferromagnetic layers made of cobalt, has the maximum frequency of the oscillations in the magnetic field parallel to the axis $OZ$. In a magnetic field directed along the axis $OX$, the Co$_{80}$Gd$_{20}$ -based spin valve has the lowest power consumption, however, the amplitude of oscillations, in this case, is very small.

4. Conclusion
In this work, the dependences of the spin-valve switching time to the antiparallel state on the spin-polarized current $t_{1-2}(J)$ and the reverse switching time on the magnetic field parallel to the anisotropy axis $t_{2-1}(H_X)$ were calculated numerically. It has been established that the most suitable material among those considered for implementing magnetoresistive random access memory is Co$_{80}$Gd$_{20}$, because the spin valve based on this material has the smallest critical switching current and the highest switching speed among the considered materials. The Fe$_{60}$Co$_{20}$B$_{20}$ -based spin valve has the shortest switching time by a magnetic field. However, the minimum switching magnetic field, in this case, power consumption is 10,000 times greater than in switching by the spin-polarized current for the Co$_{80}$Gd$_{20}$ -based spin valve. The obtained data are consistent with the results in [5].

The intervals of current and magnetic field, at which stable precession takes place, were calculated. For this case, three orthogonal magnetic field directions were considered. It is shown that to obtain a signal close to saw-tooth one, it is necessary to use a magnetic field parallel to the ferromagnetic layers anisotropy axis. At the same time, the directions perpendicular to the anisotropy axis correspond to the harmonic signal. It was found that the alloy Fe$_{60}$Co$_{20}$B$_{20}$ is the most suitable among those considered for the STNO, since the spin valve based on it has the maximum amplitude of the output signal in a magnetic field parallel to the axis $OY$. In this case, the current and field ranges are 1.5 times lower than for the cobalt-based spin valve, which has the maximum frequency of the output signal.

The calculated data presented in the paper have general recommendatory nature and illustrate the use of the theoretical model of the spin valve.

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