Parametric mechanism of magnetization reversal in FeCoB nanomagnet by a magnetic field of spin-accumulated electrons

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Abstract—Spin-polarized electrons are accumulated at nanomagnet boundaries due to the Spin Hall effect. The small magnetic field, which is induced by the spin accumulation, is able to reverse the nanomagnet magnetization when the conditions of parametric resonance are met. The features of this parametric mechanism of magnetization reversal are studied experimentally and theoretically. It is shown that the efficient parametric magnetization reversal is possible for both cases when the electron current is modulated at the Larmor frequency and when the current is not modulated at all.

Keywords—Spin-orbit torque, spin-transfer torque, parametric resonance, magnetization reversal, MRAM

I. INTRODUCTION

The reduction of recording energy is the major challenge of the present MRAM development. It is difficult to overcome the fundamental limitation for minimum required recording energy using the conventional recording methods such as the Spin Torque (ST) and the Spin-Orbit Torque (SOT). The reduction is limited by a minimum amount of the injected spin-polarized electrons, which is necessary to create a sufficient ST or SOT torque in order to reverse the magnetization of the “free” layer [1]–[6].

A possible solution for the reduction of MRAM recording energy is the use of a resonance recording method, in particular, the use of the parametric-resonance recording method. In the case of the parametric magnetization reversal, one of nanomagnet parameters is modulated at a frequency close to the resonance frequency \(\omega_r\) of the magnetization precession (Larmor frequency). Even though the amplitude of the modulated parameter is small and corresponding change of the magnetization direction is tiny (typically less than 1 degree), the resonance enhancement of the magnetization precession leads to an increase of the precession angle and eventual magnetization reversal. The parametric mechanism requires a substantially smaller spin torque for the magnetization reversal due to its resonance nature and, therefore, it can be a solution for the further reduction of the recording energy for MRAM operation [7].

For an efficient parametric enhancement, the frequency and phase matching between the pump and oscillation are important. In order to achieve the matching, the external control of the pumping parameters and the feedback tuning should be achieved. In the studied case of the current-induced magnetization reversal, it means that the magnetization direction should be modulated by the electron current, which flows through the nanomagnet. According to this requirement, three mechanisms of parametric magnetization reversal have been proposed [7], [8]. For the first mechanism, which is studied in detail in this paper, the modulated parameter is the magnetic field, which is induced by the spin-accumulated electrons. This magnetic field tilts the magnetization from its equilibrium direction. Since the amount of the spin accumulation is proportional to the electron current, the magnetization tilt is also proportional to the current as required for the parametric resonance.

For the second parametric mechanism, the modulated parameter is the anisotropy field. When a bias external magnetic field is applied perpendicularly to the nanomagnet easy magnetic axis, a change of the anisotropy field causes the change of the magnetization tilt angle. There are two efficient methods for modulation of the anisotropy field. The first method is a modulation by electrical current due to spin accumulation created by the Spin Hall effect [8]. The second mechanism is the modulation by a gate voltage due to the voltage-controlled magnetic anisotropy (VCMA) effect [9]–[11]. In a magnetic tunnel junction (MTJ), the current is proportional to the applied voltage. Therefore, for both methods the magnetization tilt is proportional to the current.

For the third parametric mechanism, the modulated parameter is the amount of spin injection. The nanomagnet magnetization can be reversed directly by a substantial spin injection, which is the mechanism of the ST and SOT MRAM recording methods [1]–[6]. However, utilizing the parametric resonance the magnetization reversal can be achieved at a substantially smaller amount of spin injection and, therefore, at a smaller recording current. The amount of the spin injection is proportional to current flowing through the MTJ. The magnetization precession is proportional to the amount of spin injection and, therefore, to the current as required for the parametric resonance.

The paper studies only the first parametric mechanism of magnetization reversal. Section 2 describes the measurement of a current-induced magnetic field in a FeCoB nanomagnet. Section 3 describes the parametric resonance in a nanomagnet induced by a RF current and Section 4 describes the parametric resonance induced by a DC current.
III. TYPICAL RECORDING CURRENT DENSITY IN MRAM IS ABOUT 50-100 mA/μm² AS A FUNCTION OF THE MAGNETIC FIELD Hz, WHICH IS EXTERNALLY APPLIED ALONG THE NANOMAGNET EASY AXIS. THE MEASURED FIELD ANGLE IS BETWEEN THE IN-PLANE COMPONENT OF H^C(I) AND TO THE DIRECTION OF CURRENT J.

II. MEASUREMENT OF THE MAGNETIC FIELD INDUCED BY SPIN- ACCUMULATED ELECTRONS IN FeCoB NANOMAGNET

When an electron current flows through a ferromagnetic nanomagnet, spin- polarized electrons are accumulated at the nanomagnet boundaries due to the Spin Hall effect [12], [13]. The magnetic field, which is induced by the spin accumulation, tilts the nanomagnet magnetization from its equilibrium direction. This magnetic field is small, but measurable. In Ref. [8] a high-precision measurement of the spin- polarization-induced magnetic field has been proposed and demonstrated.

The spin-accumulation-induced magnetic field has a complex dependency on the electron current and the external magnetic field Hz, which is applied along the magnetic easy axis. Both the amplitude and the direction of the induced magnetic field are substantially dependent on each parameter [8]. Figure 1 shows the magnitude of the in-plane component of the spin-accumulation-induced magnetic field H^C(I) and the angle between H^C(I) and the current direction, which are measured in a FeCoB nanomagnet at a small current density of 10 mA/μm². Details of the nanomagnet structure and fabrication technology are described in Ref. [8]. Equilibrium magnetization direction of the nanomagnet is perpendicular-to-plane.

The largest value of H^C(I) is ~7 G, which is measured at the smallest Hz. The H^C(I) decreases at a larger Hz and saturates at a value ~3 G. The H^C(I) is nearly parallel to the current at a small Hz, but rotates towards the perpendicular-to-current direction at a larger Hz. The substantial dependence of H^C(I) on Hz makes it possible to adjust the H^C(I) to the optimum conditions of the parametric resonance. For example, for an efficient magnetization reversal in a MTJ, the H^C(I) direction should be adjusted to be along the magnetization direction of the “pin” layer (See next section).

III. PARAMETRIC REVERSAL BY A RF ELECTRICAL CURRENT

The measured current-induced magnetic field H^C(I) is small and an external magnetic field of the same strength is far insufficient to reverse the nanomagnet magnetization. A typical recording current density in MRAM is about 50-100 mA/μm². At a current density of 70 mA/μm², the measured value of H^C(I) is only ~50 Gauss (Fig.1). The internal magnetic field H_{int}, which holds the magnetization perpendicular-to-plane, approximately equals to the anisotropy field, which was measured to be about 10 kGauss [14], [15]. Applying an external magnetic field of 50 Gauss perpendicular to the 10 kGauss turns the magnetization out of the easy axis very slightly at an angle of about 290 mdeg. The turning angle is too small and does not lead to the magnetization reversal [16].

The magnetization reversal can occur under such a small magnetic field only when the conditions of the parametric resonance are met. For example in the case when the electrical current is modulated at a RF frequency close to the magnetization-precession frequency. As a consequence, the current-induced magnetic field is modulated as well and is in a resonance with the magnetization precession. As a result, the precession is resonantly enhanced and the precession angle becomes larger after each oscillation period until the magnetization reversal occurs.

Figure 2 is the schematic diagram, which explains the mechanism of the enhancement of the magnetization precession by the parametric resonance. Figure 2(a) shows the initial states, at which the magnetization of the nanomagnet is perpendicular to the plane (along the z-axis) due to the Perpendicular Magnetic Anisotropy (PMA). There is an intrinsic magnetic field H_{int}, which is directed along the z-axis and which keeps the magnetization along that axis. When an electrical current flows through the nanomagnet, it creates the magnetic field H^C(I), the direction of which is perpendicular to H_{int} (along the x-axis in Fig.2b).

The total magnetic field H_{total}, which is induced by the nanomagnet, is a vector sum of H_{int} and H^C(I). As soon as the H^C(I) is applied and the direction of H_{total} becomes different from the magnetization direction, the magnetization precession starts around the H_{total}. At this moment, the precession angle is the angle between the directions of the magnetization and the H_{total}. As was mentioned above, the angle φ is very small, about a hundred millidegrees. After a half of the precession period, the magnetization rotates by an angle 2φ with respect to the z-axis (Fig.2c). At this moment the direction of H^C(I) is reversed and the inclination of H_{total} with respect to the z-axis is reversed as well, but the absolute value of the inclination angle still remains equal to φ (Fig.2d). In total, the angle between the magnetization and the H_{total} becomes 2φ+φ=3φ (Fig.2e) and, therefore, the precession angle becomes 3φ. During the following precession, the angle between the magnetization and the z-axis increases and becomes 3φ+φ=4φ after a half period of the precession (Fig.2h). This means that in the case when the oscillation of the H^C(I) is synchronized with the magnetization precession, at each precession period the precession angle increases by an angle of 4φ. Even though the initial field-inclination angle φ might be small, the precession angle becomes large within a short time due to the parametric pumping of the precession.

The Landau- Leifshitz equation with an oscillating parametric magnetic field was analytically solved and analyzed in Ref. [7]. Similar to the schematic explanation of Fig.2, the analytical solution predicts a substantial torque,
which is induced parametrically even by a relatively small oscillating magnetic field.

IV. PARAMETRIC REVERSAL BY A DC ELECTRICAL CURRENT.  
POSITIVE FEEDBACK LOOP FOR ENLARGEMENT OF PRECESSION ANGLE.

In the previous section, the parametric resonance has been described for the case, when the oscillation frequency of the external magnetic field is very close to the frequency \( \omega_h \) of the magnetization precession. The closeness of both frequencies is the key for the resonance enhancement of the magnetization precession. When the frequency of the external field is even slightly detuned from the resonance condition, the dephasing occurs and the effect of the parametric precession pumping vanishes [7].

In this section another mechanism of the precession enhancement by the parametric resonance is described. In this mechanism there is no external parameter, which is modulated at the resonance frequency (the Larmor frequency). The key mechanism for this type of parametric enhancement is the positive feedback loop. The magnetization precession itself creates an oscillating magnetic field, which parametrically enhances the same magnetization precession. As a result, a small oscillation enhances itself and grows over time until the magnetization reversal occurs. Since the magnetic field of the parametric enhancement is originated by the magnetization precession itself, it is always in a perfect phase and frequency match with magnetization precession. A small thermal fluctuation seeds the process and initializes the feedback loop for the growing magnetization precession.

This effect is only possible in a magneto-resistive structure, whose resistance is modulated by the magnetization precession. An example of such a structure, which is shown in Fig.3, is a magnetic tunnel junction (MTJ), which magnetization is in-plane in the "pin" layer and is perpendicular to the plane in the "free" layer. The magnetization of the "pin" is firmly fixed by a strong magnetic anisotropy. The magnetization precession of the "free" layer (Fig.3a) modulates the resistance of the MTJ (Fig.3b). Under a DC voltage applied to the MTJ, the electrical current is modulated at the precession frequency \( \omega_h \) (Fig. 3c). The electrical current induces the magnetic field \( H^{(CI)} \) (Fig.3d), which is also modulated at \( \omega_h \) and, therefore, parametrically enhances the initial magnetization precession (Fig.3a).

In the following the parametric torque induced by a DC current is calculated in a MTJ, in which the equilibrium magnetization direction is in-plane in the "pin" layer and perpendicular- to- plane in the "free" layer (Fig.3). Assuming the magnetization of the "pin" layer is fixed along the \( x \)-axis, only the \( x \)-component of magnetization of the "free" layer determines the MTJ resistance. A random thermal oscillation is parametrically amplified by the oscillating magnetic field \( H^{(CI)} \), which is induced by the oscillating spin accumulation. On the other hand, the precession of magnetization modulates the current and, therefore, the spin accumulation and \( H^{(CI)} \). It makes a positive feedback loop.

At the precession angle \( \theta \), the oscillation of the \( x \)-component of the magnetization of the "free" layer (fig.3a)

\[
M_x = M_{\text{free}} \cdot \sin(\theta) \cdot \sin(\omega t)
\]

modulates the resistance \( R \) of the MTJ (Fig.3b) as:

\[
R = R_0 \left( \frac{R_{11} - R_{1\uparrow\downarrow}}{R_0} \right) \frac{1 - k_{\text{sat}} \sin(\theta) \cdot \sin(\omega t)}{R_0} = R_0 \left[ 1 - k_{\text{sat}} \sin(\theta) \cdot \sin(\omega t) \right]
\]

where \( R_0, R_{11}, R_{1\uparrow\downarrow} \), are the MTJ resistance, when the "free" layer is perpendicular, antiparallel and parallel to the "pin" layer; \( k_{\text{sat}} = \frac{R_{1\uparrow\downarrow} - R_{1\uparrow\downarrow}}{R_0} \) is the magnetoresistance.

When a DC voltage \( U_{\text{DC}} \) is applied to the MTJ, the current is modulated by the resistance oscillation (Fig.3c) as

\[
I = \frac{U_{\text{DC}}}{R} \frac{I_{\text{DC}}}{1 - k_{\text{sat}} \sin(\theta) \cdot \sin(\omega t)}
\]

The measurement of Ref. [7] indicates that in a FeCoB nanomagnet is linearly proportional to the current for a small or moderate current density (<50 mA/\( \mu m^2 \)):

\[
H^{(CI)} = \zeta I = \frac{\zeta \cdot I_{\text{DC}}}{1 - k_{\text{sat}} \sin(\theta) \cdot \sin(\omega t)}
\]
where $\zeta$ is measured to be $\sim 0.3-0.7 \text{ G/(mA/\mu m}^2\text{)}$ and can be adjusted by $H_z$ (See Fig.1).

In the case when the magneto resistance is small, $MR_k = 1$, the amplitude of the oscillating current-induced field $H_{RF}^{(CI)}$ can be expressed as:

$$H_{RF}^{(CI)} = \zeta \cdot I_{DC} \cdot k_{MR} \sin(\theta)$$  \hspace{1cm} (5)

The oscillating field $H_{RF}^{(CI)}$ creates the parametric torque (See Fig.2). Since the oscillation of $H_{RF}^{(CI)}$ is exactly at the same frequency as the magnetization oscillation $\omega_L = \omega$, there is no dephasing over time and the parametric torque can be calculated as [7]:

$$\left(\frac{\partial \theta}{\partial t}\right)_{\text{param}} = \gamma \cdot H_{RF}^{(CI)} = \gamma \cdot \zeta \cdot I_{DC} \cdot k_{MR} \sin(\theta)$$  \hspace{1cm} (6)

where $\gamma$ is the efficiency of the parametric pumping [7].

The parametric torque of Eq.(6) is linearly proportional to the magneto-resistance $k_{MR}$, the DC current $I_{DC}$ and the parametric pumping efficiency $\gamma$. The parametric torque is absent at an equilibrium ($\theta = 0$) and increases with an increase of the precession angle $\theta$. Magnetization is reversed by the DC current when the total torque is positive for any precession angle ($\theta \neq 0$):

$$\left(\frac{\partial \theta}{\partial t}\right)_{\text{param}} - \left(\frac{\partial \theta}{\partial t}\right)_{\text{damp}} > 0$$  \hspace{1cm} (7)

where $\left(\frac{\partial \theta}{\partial t}\right)_{\text{damp}}$ is the precession damping torque [7].

V. CONCLUSION

When an electrical current flows through a nanomagnet, the spin- polarized electrons are accumulated at its boundaries due the Spin Hall effect. The magnetic field, which is induced by the spin accumulation, can reverse the magnetization of the nanomagnet if the conditions of the parametric resonance are met.

The magnetic field is small, but measurable. At a current density of 10 mA/\mu m$^2$ the measured magnetic field $H_{RF}^{(CI)}$ is about 7 Gauss. $H_{RF}^{(CI)}$ is relatively small. For example, a static external magnetic field of the same magnitude affects the nanomagnet magnetization very weakly and its effect is barely noticeable, because the magnetization direction is kept along its easy magnetic axis by a substantially stronger internal magnetic field, which is about 10 kGauss. However, when the electrical current, which flows through the nanomagnet, and, therefore, $H_{RF}^{(CI)}$ are modulated at a frequency close the resonance frequency $\omega_L$ of the magnetization precession, even the small magnetic field $H_{RF}^{(CI)}$ is able to enhance the magnetization precession and even to reverse the magnetization direction.

The most unique feature of parametric pumping is the ability to induce the magnetization precession and the magnetization reversal by a DC electrical current when there is no external parameter modulated at the precession frequency. This unique effect occurs only in a magneto-resistant structure when the electrical current is modulated by the magnetization precession and the modulated current creates the magnetic field $H_{RF}^{(CI)}$, which parametrically enhances the same precession. There is a positive feedback loop, which is able to enhance the precession of a tiny thermal oscillation until a magnetization reversal occurs.

The magnetization- reversal mechanisms are very different between the studied parametric torque and the conventional torques: the Spin-Torque (ST) and the Spin-Orbit Torque (SOT). This opens an opportunity for a further optimization of the existing MRAM and an opportunity for an extension of the range of the MRAM applications. The effectiveness of the ST and SOT can be improved only by an increase of the injected amount of spin-polarized conduction electrons from the "pin" to the "free" layer. The number of...
possibilities for such improvement is very limited. In contrast, the parametric torque can be improved by an optimization of the positive feedback loop and by a reduction of the phase-match problem. There are much more possibilities for such an improvement.

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