Switching spin valves using rf currents

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(Received 1 November 2005; accepted 12 March 2006; published online 12 May 2006)

We show that magnetization reversal in spin-injection devices can be significantly faster when using a chirped rf current, rather than a dc, pulse. Although one can use a simple sinusoidal rf pulse, an optimized series of alternating, equal-amplitude, pulses of varying width (a digitized approximation to a chirped rf pulse) produces more efficient switching. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2199456]

There has recently been a surge of interest in a new form of electronics, collectively called spintronics,[1] where the operation of individual device elements is due to their interaction with a spin polarized current. Here we focus on devices that involve a spin polarized current applied perpendicular to the easy axis of a magnetic material and examine the optimal strategy to reverse (switch) the magnetization.

It is well known that the fastest way to switch the magnetization direction in conventional devices is via a uniform rotation; there are two known ways to effectively produce such switching. The first can be called *precessional switching* and the second will be referred to as *resonant switching*. In the first of these an external magnetic field pulse is applied perpendicular to the easy axis. This creates a uniform Larmor precession in a plane perpendicular to the applied field. Clearly the applied field must be much larger than the effective anisotropy field. The second approach involves the application of a rf pulse. While it was shown experimentally by Thirion *et al.*[2] that rf fields can be used together with dc fields to lower the values of dc field needed for switching, it was thought that switching with pure rf fields is impractical due to the excitation of the Suhl instability,[3] which couples a uniform rotation to inhomogeneous spin waves. However, we have recently shown[4] that the Suhl instability can be effectively suppressed by varying such parameters as the object size and the applied fields. In this letter we will show how the idea of switching with rf fields can be applied to the spin valves.

The behavior of magnetic systems under the influence of a spin polarized current has typically been modeled using a modified Landau-Lifshitz[5] equation (here we assume that the system can be approximated by a single spin which is discussed further below):

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{h}, \tag{1}$$

where $\mathbf{m}$ is the magnetization, γ is the gyromagnetic coefficient, and $\mathbf{h}$ is an effective magnetic field. We take this effective field to have the form

$$\mathbf{h} = \mathbf{h}^{\text{true}} + \frac{\mathbf{m}}{M_s} \times (\beta \mathbf{h}^{\text{true}} - a_J \mathbf{I}), \tag{2}$$

where $\mathbf{h}^{\text{true}}$ accounts for "true" external and internal (exchange/anisotropy) fields, β is a damping coefficient, and M_s is the saturation magnetization; the interaction between the magnetization and the electrical current has been modeled here as a *spin transfer torque*,[6–9] $(\gamma a_J / M_s)\mathbf{m} \times (\mathbf{m} \times \mathbf{I})$, where $\mathbf{I}$ is the polarization of the current and a_J is an empirical factor measuring the strength of the coupling (in units of magnetic field[4] where 1000 Oe corresponds to 10^8 A/cm^2).

We start by considering systems with uniaxial anisotropy; similar results can be obtained for the shape anisotropy. We introduce a coordinate system in which the z axis lies along the easy magnetization axis.

In the resonant switching strategy,[10] a small rf field is applied to the system. For optimum response the frequency of this field must generally be "chirped" in such a way that it tracks the angle dependent resonant frequency (since anisotropy is present, the resonant frequency depends on the angle the magnetization forms with the easy axis). Although the field can be applied in the same direction as with the uniform rotation mode (i.e., perpendicular to the direction of the total magnetic field), the analytical calculations are simplest if circular polarization is assumed, with the result that the phase is shifted by $\pi/2$ with respect to the instantaneous direction of the magnetization. With this strategy the switching time is quite short and this time does not depend on the anisotropy constant. In resonant switching one needs only small effective fields.

When rf currents (rather than rf fields) are used to facilitate switching, the time dependent magnetization can be described as

$$M_x = M_s \sin(\gamma a_J t)\sin[\varphi(t)],$$

$$M_y = -M_s \sin(\gamma a_J t)\cos[\varphi(t)],$$

$$M_z = M_s \cos(\gamma a_J t), \tag{3}$$

$$\varphi(t) = K\frac{\sin(\gamma a_J t)}{a_J M_s} + \gamma H_0 t, \tag{4}$$

with the components of the rf current given by

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$$I_x = -\cos(\gamma a_J t)\sin[\varphi(t)],$$

$$I_y = \cos(\gamma a_J t)\cos[\varphi(t)], \tag{5}$$

$$I_z(t) = \sin(\gamma a_J t),$$

here K is the anisotropy coefficient and H_0 is the dc field which is applied along the z axis (note a dc field is not a requirement for switching and the switching time does not depend on either K or H_0). While being theoretically the most effective method to produce switching, how to constructing a polarization current with this time dependence is an open question, since in devices studied to date it is determined by the magnetization of one or more "fixed" layers. We offer a strategy to construct an alternative, slightly less effective method below.

A conventional spin valve consists of two layers, a thin one (the free layer) and a thick one (the source), separated by a nonmagnetic (injection) layer. The thick layer determines the polarization of the current, while the free layer determines whether the system is going to be in the low resistance (magnetization of the free layer parallel to the magnetization of the source layer) or in the high resistance (magnetization of the free layer antiparallel to the magnetization of the source layer) state. Switching occurs when a sufficiently strong current is applied. Unfortunately switching requires that the magnetization of the free layer not be entirely parallel or antiparallel to the magnetization of the free layer and therefore to the direction of polarization of the current. The cause for such misalignment is thought to arise from finite-temperature fluctuations. The switching of this configuration is explicitly nonuniform in nature.

An alternative configuration was proposed by Kent *et al.*[11] In this configuration there is a second "source" layer, with its magnetization oriented perpendicular to the magnetizations of the other two layers and parallel or to the direction of the current. In this case the magnetization switching is accomplished by applying a current with the polarization determined by the magnetization of this second source layer. One of the significant advantages of this latter configuration is that it does not rely on initial thermal excitation; it also allows for resonant switching with rf currents. The simplest way is to use a sinusoidal rf current. While such a configuration is not the most effective one (e.g., the current-induced torque vanishes at one point during the rotation), we will show numerically that it is still advantageous to use a rf current rather than a dc.

Here we will use parameters similar to those used by Kiselev *et al.*[12] in which the free layer is 2 nm thick. The layer is deposited from Permalloy and approximates an ellipse with principal diameters 130×70 nm^2. We assume that there is an exchange interaction acting between the layers. We take $A=1.3\times 10^{-6}$ erg/cm, a typical value for the exchange stiffness of Permalloy; however, we use $M_s = 680$ emu/cm^3 for the saturation magnetization, which is lower than the accepted value, but provides a better fit to the experimental results[1] (a result that may arise from the Cu layer separating the thick and thin magnetic layers). In all configurations analyzed here, an external magnetic field is assumed present that cancels the fields from the source layers. The coordinate system is chosen such that the easy axis is parallel to the z axis with the magnetic layers lying in the y-z plane; the current direction and polarization are along the x direction. In our case a current of 1 mA should correspond to $a_J \cong 144$ Oe, and the damping coefficient β is taken as[9] 0.014.

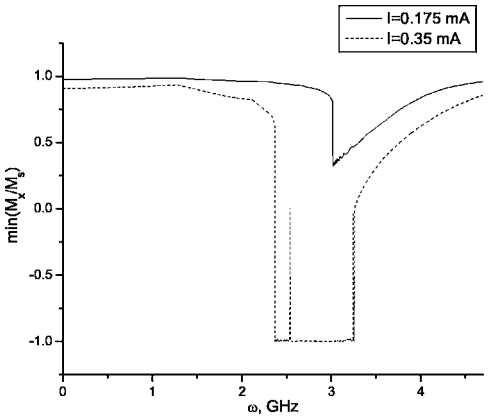

FIG. 1. Minimal value of M_z/M_s as a function of the frequency of rf current.

We used two models to represent the thin and thick layers; a *multispin* model, with each of the magnetic layers represented by an array of individual magnetic dipoles (around 20 000 in total), and a *macrospin* model, where the thick layers are assumed to be uniformly magnetized and static, while the free layer is described by a single spin, rotating under the influence of the field arising from the thick layer, the external current, and the anisotropy field. The shape anisotropy field in the thin film is described by using the numerically calculated demagnetization tensor for an ellipse. This is somewhat different from the macrospin approach used earlier;[13] in both cases it was assumed that the free layer is an ellipse, and the value of the magnetic field due to the thick layer was determined experimentally. Comparing various results obtained by using the macrospin model (resonant frequencies, switching speeds) with those from the multispin model shows that in this particular case the macrospin model should be a good approximation.

We first attempt to switch the magnetization from $+M_s\hat{z}$ to $-M_s\hat{z}$ using only a dc. Our analysis of dc driven switching shows that the onset is at 0.62 mA. If, on the other hand, we use rf currents with a sinusoidal time dependence, switching is possible for much smaller currents; however, one has to choose an appropriate frequency in order to obtain switching. In Fig. 1 we show the minimum value of M_x/M_s as a function of the frequency. For our configuration the Larmor resonant frequency is 5.5 GHz, so it is apparent that switching is possible for a range of frequencies, all of them significantly smaller than the Larmor frequency. The explanation for this phenomenon is that in objects with shape anisotropy the resonant frequency depends on the angle between the magnetization vector and the anisotropy axis; for large precession angles this frequency can differ significantly from the small-angle Larmor frequency. Assuming the magnetization is initially aligned along the easy axis, the resonant frequency will in general decrease as the magnetization tips away from the easy axis; therefore the optimal switching frequency will clearly be lower than the small-angle resonant frequency.

Calculating the lowest frequency that allows switching as a function of the rf current amplitude, we obtain a nearly linear behavior of the form

$$\omega = 3.74 - 4.015I. \tag{6}$$

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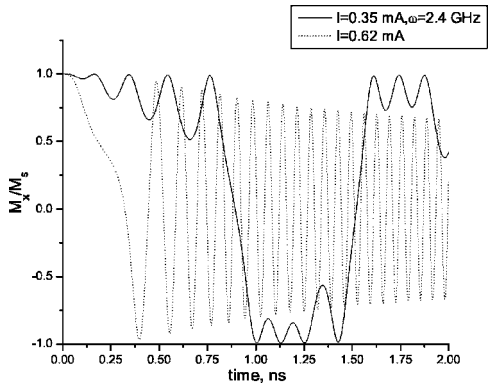

FIG. 2. M_z/M_s as a function of time for switching with rf current and dc.

For currents smaller than $I=0.21$ mA switching no longer occurs; on the other hand, there is no lower limit (in the absence of damping) with the chirped-pulse strategy. However, this current is still almost three times lower than the dc needed to switch this system.

In Fig. 2 we show the time required for switching M_z with dc versus rf currents. In both cases, if the currents are not turned off the system will continue to oscillate from up to down. A dc allows for faster switching (albeit with much higher currents), but it also stays in the region where M_z is negative for only very short times, which would require very precise pulse lengths. On the other hand, switching via rf currents results in the system having negative values of M_z approximately 15 times longer than in the case when dc are used.

As with the magnetically driven case, one anticipates that chirping the rf current will yield more efficient switching. However, rather than using a constant-amplitude sinusoidal rf pulse with a chirped phase function, we have found that a series of pulses of equal magnitude, alternating sign, and varying width produces very stable switching; such a wave form might be synthesized digitally in practice. The associated pulse widths are chosen so as to maximizes the decrease in M_z: From Eqs. (1) and (2) it follows that the rate of change of M_z due to the applied current is

$$\frac{dM_z}{dt} = \gamma a_J(t)\frac{M_x M_z}{M_s}, \tag{7}$$

hence if we wish to minimize this term with the chosen wave form, the sign of a_J should be opposite to that of $M_x M_z$.

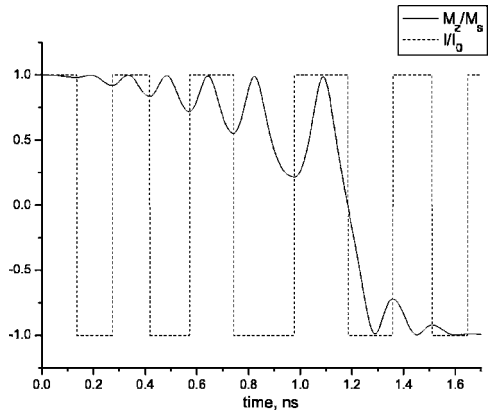

FIG. 3. The magnetization M_z/M_s as a function of time for switching with an optimized sequence of square pulses with amplitude $I_0=0.17$ mA.

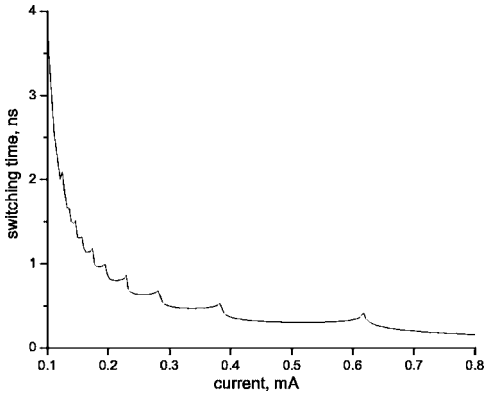

FIG. 4. Switching time as a function of current amplitude.

In Fig. 3 we present the resulting pulse sequence and the behavior of M_z/M_s versus time for the case where the current amplitude is 0.17 mA. Figure 4 shows a switching time, defined as the time it takes for the system to reach negative values of M_z/M_s as a function of the current amplitude for the chirped pulse. The graph contains a few points ($I=0.62$, 0.38, 0.28 mA) where the derivative is discontinuous; each of these points corresponds to an extra pulse needed to perform the switching. For the currents above 0.62 mA the switching is accomplished via a single square pulse and is undistinguishable from the use of dc; for the currents between 0.62 and 0.38 we need to apply two square pulses with opposite magnitude and so on. The switching process as a whole was numerically shown to be stable with respect to approximately 20% perturbation in the pulses' shape and magnitude.

In conclusion we have shown that the fastest available methods for switching traditional magnetic devices (precessional and chirp resonant) can also be used for spin valves. While implementing such methods is demanding, we have shown that some simpler methods, utilizing a sinusoidal rf current pulse or an optimized sequence of sequence of alternating current pulses, can lower the required switching currents.

This work was supported by the National Science Foundation under Grant Nos. ESC-02-24210 and DMR 0244711.

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