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# Spin-transfer-induced precessional magnetization reversal

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A magnetoelectronic device is proposed in which a spin-current pulse produces a rapid reversal of the magnetization of a thin film nanomagnet. A spin-transfer torque induces the reversal and the switching speed is determined by the precession frequency of the magnetization in a thin film element's demagnetization field. Micromagnetic simulations show that this switching occurs above a threshold pulse current and can be faster than 50 ps. In contrast to present spin-transfer devices, the switching does not require an initial fluctuation or deviation of magnetic layers from collinear alignment and is far more energy efficient. This device operates at room temperature and can be realized with present-day magnetic nanostructure technology. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1739271]

Magnetic devices for information processing and storage require ultrafast manipulation of the magnetization of nanometer scale magnetic elements. Present day applications use magnetic field pulses generated by electrical current flow through small coils and wires. Examples are the recording heads used to write data on magnetic hard drives and magnetic random access memory, in which current carrying wires close to magnetic elements generate magnetic fields that are used to switch the element's magnetization direction. Magnetic fields from wires decay slowly in space, which can limit information storage density, and lead to coupling between magnetic bits, i.e., a bit will experience magnetic fields from the wires addressing neighboring bits. Recently it has been demonstrated that a spin-current flowing directly through a nanomagnet can switch its magnetization direction by a mechanism called spin transfer.[1–3] Spin transfer relies on a strong, short-range interaction between a spin current and the background magnetization of a nanomagnet. Spin-transfer induced switching therefore has important advantages over field induced switching and will likely form the basis for a new generation of magnetic information storage devices.

Present spin-transfer devices consist of current perpendicular to the plane magnetic metallic multilayer nanopillars with at least two magnetic layers, separated by a nonmagnetic metal.[3–6] The magnetizations of the layers are *initially collinear*. The two possible states of either parallel or antiparallel alignment have different resistances because of giant magnetoresistance (GMR). One magnetic layer typically has its magnetization pinned by virtue of being thicker or exchange coupled to an antiferromagnetic. The second magnetic layer is known as the free layer and its magnetization direction can be switched relative to the former. Its thickness is generally 1–10 nm and lateral size is 30–100 nm. A spin current can switch the free layer direction. The switching is understood through a model proposed by Slonczewski in which the torque on the free layer magnetization is proportional to the spin current and in a direction given by $\hat{m}\times(\hat{m}\times\hat{m}_p)$, where $\hat{m}$ and $\hat{m}_p$ are the magnetization direction of the free and pinned magnetic layers, respectively.[1] Analysis and micromagnetic calculations based on this model show that magnetization reversal requires an initial deviation of the layers from strictly parallel or antiparallel alignment and proceeds through many precessional oscillations before reaching a static magnetization state.[7] The resulting reversal is thus considerably longer than one precession period and typically of the order of nanoseconds.[8] Further, if the initial deviation is produced by thermal fluctuations of the nanomagnet the switching is stochastic resulting in a broad distribution of switching times.[7]

In this letter we present a device concept in which a spin-current pulse can induce a rapid precessional reversal of the magnetization of a thin film nanomagnet.[9] The switching speed is determined by the precession frequency of the magnetization in a thin film element's demagnetization field. Micromagnetic simulations demonstrate that the switching time can be less than 50 ps. In contrast to present spin-transfer devices, the method does not require multiple precessions or a fluctuation to initiate the reversal and requires less energy. In fact, the reversal can occur in a single 180° rotation of the magnetization for appropriate current pulses.

The basic idea can be illustrated in a geometry in which the fixed layer magnetization direction $\hat{m}_p$ (FM1) is aligned *perpendicular to the plane* of the layer and the free layer has in-plane magnetization $\hat{m}$ (FM2). These layers are separated by a nonmagnetic layer (NM1), as shown in Fig. 1. A third ferromagnetic layer (FMref) separated from FM2 by a nonmagnetic layer (NM2) is used for readout of the magnetic state of FM2 and will be discussed in greater detail below. Since the spin torque is in a direction given by $\hat{m}\times(\hat{m}\times\hat{m}_p)$, this torque acting on the magnetization of the free layer causes the magnetization of the latter to rotate out of the plane. As the thickness of the free layer is less than its lateral dimensions, the presence of an out-of-plane component of magnetization leads to a large demagnetization field perpendicular to the plane of the layer. This demagnetization field forces the magnetization vector of the free layer to precess about a direction normal to the film plane. The rate of precession is determined by the demagnetization field, which reaches a maximum ($\sim 4\pi M$) when the layer magnetization is perpendicular to the plane of the film. Thus the time for a 180° rotation of the magnetization will be about

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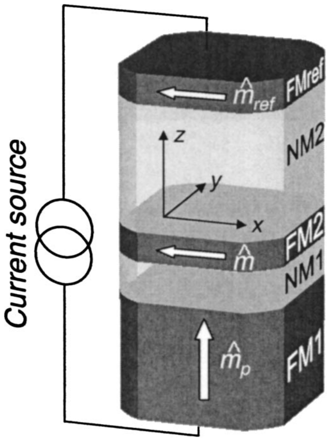

FIG. 1. Schematic of a current perpendicular to the plane spin-transfer device. FM1 is the pinned magnetic layer in the device and is magnetized perpendicular to the plane of the layer, along the current direction. FM2 is separated from FM1 by nonmagnetic layer (NM1) and is reversed by magnetization precession. FMref is a reference magnetic layer, separated from FM2 by a nonmagnetic layer (NM2) and is used to read the magnetic state of FM2.

$T \approx 1/(\gamma 4M)$ where $\gamma$ is the gyromagnetic ratio. For a transition metal thin film element (Co, Fe and Ni and their alloys) $4\pi M \sim 1$ T and thus $T \sim 20$ ps.[10] This motion is illustrated in Fig. 2.

We now present a model for spin-current induced precessional magnetization switching. The Landau–Lifshitz–Gilbert equations of motion for the free layer including a spin-current induced torque predicted by Slonczewski is

$$\frac{d\hat{m}}{dt} = -\gamma \hat{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma a_I \hat{m} \times (\hat{m} \times \hat{m}_p). \qquad (1)$$

For illustration purposes we assume that the free layer behaves as a single magnetic domain and that the spin-polarized current is associated with FM1, i.e., that the reference layer (FMref) does not affect the magnetization dynamics. $\mathbf{H}_{\mathrm{eff}}$ is the effective field, including demagnetization fields, $\mathbf{H}_{\mathrm{eff}} = \mathbf{H} + H_A(\hat{m} \cdot \hat{x})\hat{x} - 4\pi M(\hat{m} \cdot \hat{z})\hat{z}$, where $\mathbf{H}$ is the applied external field (taken to be zero in the following discussion), $H_A$ is the anisotropy field ($H_A = 2K/M$, where $K$ is the uniaxial anisotropy constant), $\hat{z}$ is the film normal. The second term on the right hand side is the Gilbert damping term and $\alpha$ is the Gilbert damping parameter ($\alpha \ll 1$). The last term incorporates the spin-transfer effects. The prefactor, $a_I$, depends on the current, the polarization of the current and the angle between the free and pinned magnetic layers, $\hat{m}$ and $\hat{m}_p$, $a_I = \hbar I/(eMV) g(P, \hat{m} \cdot \hat{m}_p)$. The first term leads to a precession of the magnetization about the effective field and the second term causes this precession to decay with time. The spin-transfer term can either amplify or attenuate the motion, depending on the direction of current flow, i.e., the sign of $I$. We determine the response of $\hat{m}$ to a current pulse by numerical integration of Eq. (1).

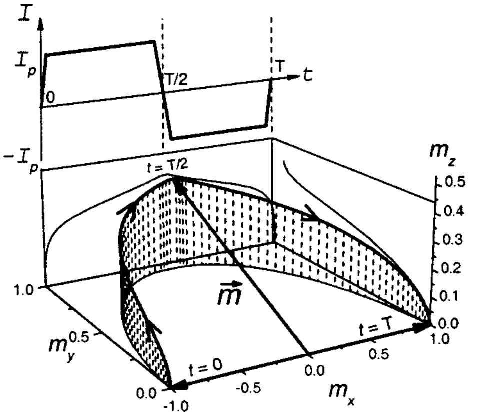

FIG. 2. Simulation of magnetization reversal in the presence the alternating current pulse shown in the upper part of the figure. The magnetization initially moves out of the plane of the thin film nanomagnet (FM2) which generates a demagnetization field about which the magnetization rotates. The second part of the pulse ($t > T/2$) forces the magnetization back into the film plane stopping the precession.

We consider a pulse shown in Fig. 2 that consists of an alternating current. The positive going part produces a torque that forces the magnetization of the free layer out of the film plane. This generates a demagnetization field mainly perpendicular to the film plane about which the magnetization precesses. The negative going part of the pulse pulls the magnetization back into the film plane stopping the precession in the desired state. The figure shows a simulation of a Co free layer ($M = 1400$ emu/cm$^3$, $\alpha = 0.01$) with an in-plane uniaxial anisotropy $K = 7 \times 10^5$ erg/cm$^3$ ($H_A = 0.1$ T) that is 3 nm thick, with lateral dimensions of 30 nm by 60 nm. This element has sufficient volume and anisotropy to be thermally stable over long time periods at room temperature (KV $= 90$ kT). The pulse current is $I_p = 5$ mA and $P$ is 0.4. Under these conditions the reversal time T is 50 ps.

The characteristics of spin-transfer induced precessional magnetization reversal are distinct from that of spin-transfer induced switching that have been the subject of previous analysis.[7,11,12] In particular, the dependence of the threshold current on the in-plane magnetic anisotropy, the speed of switching and the energy efficiency differ considerably. The threshold current for precessional reversal, $I_T$, *goes to zero* as the in-plane uniaxial anisotropy goes to zero, which agrees with the phase diagram determined for a free layer with easy plane anisotropy [see Fig. 2(b) of Ref. 11]. We compute the current threshold by numerical integration of Eq. (1), with $I_T$ defined as the pulse current for which the reversal time is 1 n. The dependence of $I_T$ on $H_A$ is shown in the inset of Fig. 3. For comparison, for the case of an in-plane magnetized pinned layer, the threshold for switching from parallel to antiparallel alignment is given by $a_T = \alpha(H_A + 2\pi M)$, and thus the current threshold is $I = \alpha 2\pi e M^2 V/\hbar g(P,1)$ when $H_A$ is zero (Fig. 3 inset). Hence, $I_T$ can be less or greater than the threshold current required for switching with an in-plane magnetized pinned layer depending on the in-plane uniaxial magnetic anisotropy, magnetization and damping of the layer. As with switching with an in-plane pinned magnetic layer, decreasing the volume or magnetization of the free layer, increasing the current-spin polarization (i.e., using a magnetic layer with a higher degree of spin polarization) and decreasing the damping coefficient all serve to reduce the current switching threshold. Note that there is only a small variation of $I_T$ with the damping coefficient (i.e., with $H_A = 0.1$ T reducing alpha by a factor of 10 from 0.01 to 0.001 leads to a reduction in $I_T$ by 20 %).

A major advantage of our device concept is ultrafast magnetic switching. For pulse currents larger than the thresh-

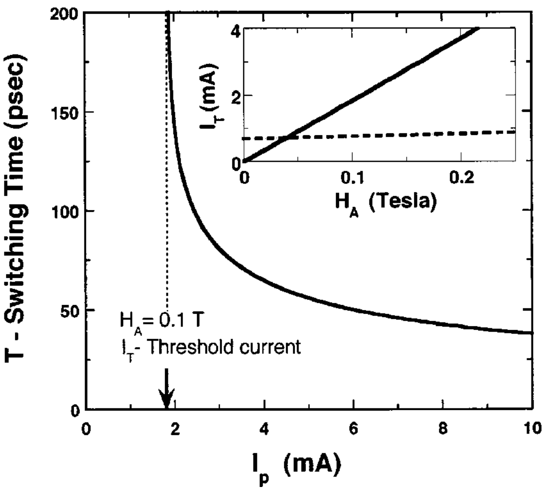

FIG. 3. Switching time vs pulse current, $I_p$. The inset shows the variation of the threshold current, $I_T$, with the in-plane uniaxial anisotropy field, $H_A$. The dashed line in the inset is the threshold current for the case in which the pinned layer is magnetized in plane and the switching is from the parallel to antiparallel magnetic state.

old current the switching time decreases rapidly, as shown in Fig. 3. For large pulse currents the switching time approaches the precessional limit $T \approx 1/(\gamma 4M)$, which is orders of magnitude faster than present spin-transfer devices. The reason for the increased switching speed is that in present spin-transfer devices the spin-current induced torque essentially amplifies small fluctuations of the magnetization and the reversal time is thus proportional to the damping coefficient.[7] In precessional magnetization reversal the switching time is determined by the layer magnetization and depends weakly on the damping coefficient. Further, spin-transfer induced precessional reversal will be more reliable, since an initial fluctuation is not required for reversal.

This device concept is also significantly more energy efficient. For example, for $I_p = 5$ mA reversal occurs in 50 ps and for a 10 Ω device $10^{-14}$ J is required. This can be compared to the energy required to switch a device in which the pinned and the free layer magnetizations are initially aligned along the same axis. A similar current would lead to an average switching time of ~5 ns,[7] with a power dissipation a factor of 100 greater, or for the 10 Ω device, $10^{-12}$ J. In addition, because the pulse is on only very briefly, in spite of the large current densities 3 A/$\mu$m$^2$, electromigration should not be a significant problem. (We note that we have operated spin-transfer devices at current densities five times this value for extended times ~days with no device damage.[5])

While we have illustrated this switching for a particular pulse shape (Fig. 2), many different pulse forms would perform the same function. For example, the pulse can be inverted, first negative current then positive. Note the switching time will be different because of the angular dependence of the spin-torque term [i.e., $g(P, \hat{m} \cdot \hat{m}_p)$]. The pulses can have longer rise and fall times. Also a simple positive (or negative) going pulse above the threshold current can initiate the reversal. In this case even shorter pulse times are possible and the magnetization may precess several times about its final reversed state. This simple pulse would have the advantage that less than half the energy is required and the disadvantage that a longer time is required for the magnetization to "settle" into its new state.

In a simple implementation in a magnetic memory device a reference readout layer (FMref in Fig. 1) separated from the free layer by a nonmagnetic layer (NM3) is required. The readout magnetic layer has a magnetization direction $\hat{m}_{\mathrm{ref}}$ with a fixed magnetization direction. For example, the readout magnetic layer can be exchange biased to an antiferromagnetic layer. The resistance of the device will then be sensitive to the relative orientation of the magnetization directions of the free layer and reference layer because of GMR and this can be used to readout the magnetic state of the device. Note that the reference layer will affect the spin polarization of the current and thus the magnetization dynamics. A more detailed analysis of the spin transport and magnetization dynamics that includes FMref would be necessary to optimize the device read out signal in combination with other critical characteristics, such as the switching time and threshold switching current.

The realization of such a device is well within the possibilities of present thin film magnetic material and nanofabrication technologies. Thin films with perpendicular anisotropy can be realized in multilayers, such as Co or Fe layered with Pt or Pd[13] or by using shape anisotropy, that is, using a pinned layer with thickness greater than its lateral size, such as can be obtained through deposition in track etched membrane templates.[14] Slonczewski initially proposed a device, with the magnetic layers all initially aligned along the same axis, in which spin transfer occurs by reflection.[15] Similarly, for this switching concept, it would be of great interest to realize a device in which no net current passes through FM2, i.e., in which spin transfer occurs by reflection from FM2. While this requires developing new nanofabrication methodologies, a major advantage is that higher resistance magnetic tunnel junction (~$k\Omega$) could be used to read to magnetic state of the device and the resulting output signal would be large.

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