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Magnetic susceptibility measurements as a probe of spin transfer driven magnetization dynamics

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An experimental technique has been developed to characterize spin-transfer driven magnetization
dynamics. It was tested on a nanopillar spin valve with perpendicular anisotropy by measuring the
nanopillar voltage under ac injected current (dV/dI), and ac magnetic field (dV/dH). Both the
amplitude and the sign of the signals are different which reveals the different influences of the
current and the field on the magnetization dynamics. Comparison between experiments and
macrospin simulation shows that dV/dH measurements reveal the presence of a “canted state”
demonstrating that dV/dH and dV/dI measurements are complementary techniques to probe

It is now well established that magnetization switching
or precession can be induced by spin polarized injected cur-
cent due to the spin transfer torque (STT) effect. 1,2 This topic
has been extensively studied because of the interesting phys-
cics and the potential applications for spin transfer magnetic
random access memories and high-frequency oscillators. 3–10

Most of devices studied are nanopillar spin valves or tunnel
junctions consisting of a hard magnetic layer as a polarizer
for incoming electrons and a soft one as a free layer. 3–10 The
spin angular momentum is transferred by an injected current
dc generating a torque on the free layer magnetization. For
a small or moderate injected current, hysteretic magnetization
switching can take place. For certain combination of
current and magnetic field, the STT may balance the damp-
ing torque and give rise to steady magnetization precession
in the gigahertz frequency regime. 1,6 Furthermore, other
magnetic states and dynamics have also been identified such
as fluctuations, 3 canted states, 7 and domains states. 8

The most common experiments for characterizing the
dynamical magnetic states consist in recording the differen-
tial resistance dV/dI, i.e., detecting the ac voltage response
to a small alternating current with a frequency (e.g., 1 kHz)
much lower than the magnetization precession. 3–10 The differ-
tential resistance can be written as

\[ dV/dI = R + l dR/dI. \] (1)

The first term is the dc resistance which directly probes the
magnetoresistance (MR) effect. The second term probes the
reversible processes such as steady magnetization preces-
\[ dV/dH = l dR/dH + R dI/dH. \] (2)

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The first term is related to the reversible magnetic processes
induced by the magnetic field and the second term results
from the ac current induced by the ac magnetic field. It
should be noted that in the case of low frequency excitation,
the voltage response to reversible magnetic process is in-
phase with the ac magnetic field excitation. However, the
current variation in response to the ac-magnetic field is an
inductive phenomena leading to an out-of-phase response,
i.e., a 90° phase shift. This phase property allowed us to
distinguish the two terms.

In this letter, we report a comparative study on the spin-
transfer-driven magnetization reversal and dynamics in a
nanopillar spin valve with perpendicular magnetic anisotropy
(PMA) using R, dV/dI, and dV/dH measurements. Both
voltage responses to an ac magnetic field parallel (dV/dH)\( _{\parallel} \) and perpendicular (dV/dH)\( _{\perp} \) to the dc magnetic field were measured. Dips or peaks in dV/dI, dV/dH\( _{\parallel} \), and dV/dH\( _{\perp} \)

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exhibit distinct features where some magnetic states are re-
vealed by dV/dH\( _{\parallel} \) and dV/dH\( _{\perp} \) while being almost absent in
the dV/dI signal.

The spin valve studied here, as reported earlier, 7 consis-
tes in a Pt(30 Å)/[Co(2.5 Å)/Pt(5.2 Å)]\( _{10} \)/Co(2.5 Å)/
[Co(1 Å)/Ni(6 Å)]\( _{5} \)/Co(2 Å)/Pt(30 Å) free layer spaced by a 40 Å
Cu layer. A Ta(50 Å)/Cu(300 Å) film acts as the bottom lead
and a Cu(200 Å)/Ta(50 Å) film connects the top of the pillar
to an Au top lead. Both the reference and the free layer
are PMA. The multilayer was then patterned to a 50 × 200 nm\(^2\) ellipse.

The transport measurements were performed at room
temperature. A dc magnetic field \( H_{dc} \) up to 1.5 T was applied

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perpendicular to the film plane. The dc current $I_{dc}$ was injected from a current source and the dc voltage $V_{dc}$ was measured with a nanovoltmeter, allowing us to determine the resistance $R=V_{dc}/I_{dc}$. The positive current is defined as the one flowing from the free layer to the reference layer. To measure $dV/dI$, a 50 $\mu$A current at a frequency $f=1$ kHz was applied and the generated voltage at the same frequency was measured with a lock-in amplifier. To probe $dV,dH$, a 40 Oe magnetic field at $f=10$ Hz was generated by a pair of Helmholtz coils either parallel (P) or perpendicular to the dc magnetic field, respectively. The resulting ac voltage responses at the same frequency were probed by the lock-in amplifier and only the in-phase voltage responses were considered to define $dV/dH_P$ and $dV/dH_L$. Most of the measurements focus on large negative field and large positive current region where free layer precession is expected.\(^5\)

Figure 1 shows a series of the typical curves of $R$, $dV/dI$, $dV/dH_P$, and $dV/dH_L$ as a function of $H_{dc}$ for various $I_{dc}$. Initially, the spin valve was saturated in a positive magnetic field to set the magnetization of the free layer $P$ to that of the reference layer resulting in a low resistance $R_P$. The dc magnetic field was swept down to $-5$ kOe, where the magnetization of the free layer is antiparallel (AP) to that of the reference layer, leading to a high resistance $R_{AP}$, and then swept back to 1 kOe, where the configuration is back to P. For $I_{dc}=4$ mA (corresponding to the current density $J\approx4\times10^7$ A/cm$^2$), shown in Figs. 1(a)–1(d), along the magnetic field descending branch, $R$ jumps sharply from $R_P$ to $R_{AP}$ at $H_{dc}=-1.6$ kOe, and falls to $R_P$ at $H_{dc}=-0.99$ kOe for the ascending branch. This measurement shows the hysteretic switching of the free layer magnetization between P and AP configuration. The $dV/dI$ versus $H_{dc}$ curves display similar hysteresis loops due to the absence of reversible magnetic process induced by the current, i.e., here only the $R$ term remains in Eq. (1). The $H_{dc}$ dependences of both $dV/dH_P$ and $dV/dH_L$ show only a flat baseline meaning that almost no reversible magnetic process is induced by the magnetic field.

For $I_{dc}=6$ mA, shown in Figs. 1(e)–1(h), no obvious hysteresis is observed. $R$ changes rapidly for the $H_{dc}$ between $-1.80$ and $-1.87$ kOe but slowly between $-1.87$ and $-2.10$ kOe. $dV/dI$ measurements show a large dip at $H_{dc}=-1.87$ kOe and a small one at $H_{dc}=-2.01$ kOe relative to reversible magnetic processes. The $dV/dH_P$ signal shows negative peaks similar to $dV/dI$. The $dV/dH_L$ however shows both negative and positive peaks.

For $I_{dc}=9.6$ mA, shown in Figs. 1(i)–1(l), there are more dips or peaks in $dV/dI$, $dV/dH_P$, and $dV/dH_L$ in a wide $H_{dc}$ range, corresponding to the different jumps in $R$.\(^5\) The amplitude of these peaks are different for $dV/dI$, $dV/dH_P$, and $dV/dH_L$ showing the different influence of current and magnetic field on the magnetization dynamics. It is interesting that $dV/dH_P$ and $dV/dH_L$ exhibit some small peaks for the $H_{dc}$ between $-1.66$ and $-2.83$ kOe corresponding to the undulation in $R$, while they are not visible in $dV/dI$.

The $R$ as a function of $H_{dc}$ for various $I_{dc}$ between 7.2 and 10 mA are also plotted in Fig. 1(i). It can be seen that the curves are reversible but also show plateaus that are separated by similar giant magnetoresistance (GMR) steps. Assuming these intermediate resistance plateaus represent precession states, these results would tend to show that magnetization prefers to precess with particular angles. Indeed the spin valve GMR value depends on the relative angle between the free layer moments and the reference layer that is out of the film plane. In this case the precession angle $\varphi$ can be roughly calculated from $\cos\varphi=1-2[R(\varphi-R_P)]/(R_{AP}-R_P)$.\(^{15}\) The reasons of those particular angles are not known and could be due to particular aspect of the nanoscale shape as the details of these steps varies from sample to sample. An alternate interpretation could be in terms of incoherent precession (spin waves).

Nevertheless those steps and plateaus give rise to dips or peaks in $dV/dI$ and $dV/dH$ measurements. It should be noted that different features in the dips or peaks for $dV/dI$, $dV/dH_P$, and $dV/dH_L$ indicate the influences of current and magnetic field on the magnetization precession. The magnetization dynamics results from the competition between the torque due to the magnetic field, the damping and the spin torque. In a macrospin approach magnetization precession appears when the spin torque balances the damping, a
change in $H_{dc}$ or $I_d$ will then change the angle of the magnetization precession and thus a variation in the resistance. The different signals coming from those measurements can be more clearly shown in the $(H_{dc}, I_d)$ phase diagrams.

Figures 2(a) and 2(b) show the $(H_{dc}, I_d)$ phase diagrams for $dV/dI$ and $dV/dH_{dc}$. The STT-driven precession takes place when $I_{dc} > 5.6$ mA and $H_{dc} < -1.9$ kOe. The phase diagrams for $dV/dI$ and $dV/dH_{dc}$ show similar branches which indicate the transition between one steady precession and another. However those transitions are more or less pronounced depending on the kind of excitation. One key difference is the presence of a vertical line around $-1.8$ kOe in the $dV/dH_{dc}$ phase diagram but absent in the $dV/dI$ one. It shows that the state that may be probed with $dV/dH$ only is affected by the magnetic field and not the current which highlight the fact that these three techniques are complementary. For a better understanding we performed macrospin simulations similar to the one reported in Ref. 10 to compare to the experimental data. Similar parameters were used and the anisotropy axis was by $5^\circ$ away from the normal of the film plane. Considering that the voltage changes come from GMR effect only and assuming that the hard layer is solidly fixed along the easy axis then the voltage $V$ is proportional to the magnetization component along the easy axis that will be refereed as $m_z$. As shown in Figs. 2(c) and 2(d), the vertical branch appears in the $dm_z/dH_{dc}$ phase diagram but cannot be seen in the $dm_z/dI$ phase diagram. The magnetic state related to this effect is a canted state which is a static state for which the magnetization is tilted away from the easy axis.

From this simple macrospin calculation, the plateaus in $R$ versus $H_{dc}$ and the branches in the precession region of the $dV/dI$ phase diagram cannot be explained. These may show the limit of the macrospin model and suggest the presence of nonuniform magnetic configurations.

In summary, we studied STT-driven magnetization dynamics in a nanopillar spin valve with PMA using $R$, $dV/dI$, $dV/dH_{dc}$, and $dV/dH_{dc}$ measurements, respectively. $R$ and $dV/dI$ can give the information on hysteretic magnetization switching, and $dV/dI$, $dV/dH_{dc}$, and $dV/dH_{dc}$ can probe reversible magnetization processes. Both the amplitude and the sign of the peaks in $dV/dI$, $dV/dH_{dc}$, and $dV/dH_{dc}$ show the different influence of current and magnetic field on the magnetization dynamics. The three methods are complementary and offer new ways to study the different magnetic states and their dynamic. More precisely it is shown in this paper that the canted states can be easily detected using $dV/dH$ whereas it is nearly undetectable using $dV/dI$. It should be noted that these low cost and feasible methods are not limited to perpendicular magnetization systems nor to STT devices but it can be used to probe any magnetic state which lead to a MR effect.

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