Temperature dependence of microwave voltage emission associated to spin-transfer induced vortex oscillation in magnetic tunnel junctions

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The temperature dependence of a vortex-based nano-oscillator induced by spin transfer torque (STVO) in magnetic tunnel junctions (MTJ) is considered. We obtain emitted signals with large output power and good signal coherence. Due to the reduced non-linearities compared to the uniform magnetization case, we first observe a linear decrease of linewidth with decreasing temperature. However, this expected behavior no longer applies at lower temperature and a bottom limit of the linewidth is measured. © 2012 American Institute of Physics. [doi:10.1063/1.3680091]

A spin polarized current can exert a large torque on the magnetization of a ferromagnet through a transfer of spin angular momentum.1 This mechanism offers a method to manipulate a magnetization, and potentially a stable precession and eventually reaches a stable gyrotropic motion. The complete structure (with thickness in nm) is: PtMn(15)/CoFe(2.5)/Ru(0.85)/CoFeB(3)/MgO(1.075)/NiFe(10)/Ta(7)/Ru(6)/Cr(5)/Au(200). Here, we focus on a MTJ pillar with resistance values at room temperature (RT) $R_P = 49 \, \Omega$ for the case of two parallel uniform magnetizations, and $R_{AP} = 58 \, \Omega$ for two antiparallel uniform magnetizations, corresponding to a tunnel magnetoresistance ratio (TMR) of $\approx 18\%$. The TMR ratio decreases down to 11% for the maximum positive applied current ($I_{dc} = 7\, \text{mA}$), a standard behavior of the TMR bias dependence.13,14 Note that positive current corresponds to electrons flowing from the free to the SAF layer. As concerns the temperature dependence, the TMR ratio increases up to 27% at 20 K which, again, corresponds to standard increasing ratios.14 Several samples from the same wafer were measured and similar resistance values were obtained. For zero (or low) in plane field, the remanent magnetic configuration is a vortex state. In such system with a vortex and a uniform SAF polarizer, we have shown that a large output signal can be obtained when the perpendicular component of the spin polarization $p_z$ is both parallel to the core polarity (for positive current sign) and sufficiently large.7,8 These two conditions are achieved, with the MTJ studied here, by applying a perpendicular field $H_{perp} > 3.5 \, \text{kG}$.

In Fig. 1, we report on the main features of the microwave signal associated to the spin-transfer induced gyroscopic motion of the vortex core. From the evolution with the current $I_{dc}$ of the four parameters, that are (a) the frequency $f$, (b) the linewidth $\Delta f$, (c) the integrated power $P_{int}$, and (d) the non-linear coefficient $N$, two regimes in the vortex dynamics can be clearly identified. Below a threshold current $I_{th} = 3.4 \, \text{mA}$, marked by a red line, the microwave characteristics are associated to current induced thermally activated vortex oscillations (“TA-VO”) and $P_{int}$ is below 1 nW. In this region, the trajectory of the vortex strongly depends on the disorder landscape, i.e., material defects and grains,15 which implies a complicated behavior for the frequency evolution to MTJs with uniform magnetization.4 Hence, we expect a quasi-linear dependence of $\Delta f$ with temperature.

The samples are circular MTJs of 300 nm diameter, with a 10 nm NiFe thick free layer and a synthetic antiferromagnet (SAF) that acts as in-plane uniformly magnetized spin polarizer. The frequency $f$ of the oscillations $f = \frac{49}{2\pi R_P}$ is relatively high due to the high TMR. This corresponds to a small $p_z$ value, which causes a wide linewidth. The complete structure (with thickness in nm) is: PtMn(15)/CoFe(2.5)/Ru(0.85)/CoFeB(3)/MgO(1.075)/NiFe(10)/Ta(7)/Ru(6)/Cr(5)/Au(200). Here, we focus on a MTJ pillar with resistance values at room temperature (RT) $R_P = 49 \, \Omega$ for the case of two parallel uniform magnetizations, and $R_{AP} = 58 \, \Omega$ for two antiparallel uniform magnetizations, corresponding to a tunnel magnetoresistance ratio (TMR) of $\approx 18\%$. The TMR ratio decreases down to 11% for the maximum positive applied current ($I_{dc} = 7\, \text{mA}$), a standard behavior of the TMR bias dependence.13,14 Note that positive current corresponds to electrons flowing from the free to the SAF layer. As concerns the temperature dependence, the TMR ratio increases up to 27% at 20 K which, again, corresponds to standard increasing ratios.14 Several samples from the same wafer were measured and similar resistance values were obtained. For zero (or low) in plane field, the remanent magnetic configuration is a vortex state. In such system with a vortex and a uniform SAF polarizer, we have shown that a large output signal can be obtained when the perpendicular component of the spin polarization $p_z$ is both parallel to the core polarity (for positive current sign) and sufficiently large.7,8 These two conditions are achieved, with the MTJ studied here, by applying a perpendicular field $H_{perp} > 3.5 \, \text{kG}$.

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samples is 48 nW, which is, to our knowledge, the largest
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Fig. 2(a), we focus
on

P_{int} vs
Idc
value of
D

\\[ \frac{D}{f} \left( \frac{2}{f_{v}} \right) \]

10 MHz, see Fig. 1(b))
and
N,
that is extracted from the derivative of
f
and
P_{int}
Idc
i.e.,
\N = df/dip \quad \text{vs} \quad \Idc
\\[ \text{N} = \frac{df}{dip} = \frac{df}{dIdc}(dIdc/dip), \]
varies strongly (see
Fig. 1(d)). At the threshold current, \( I_{th} \), \( f \) undergoes a sharp
change, \( P_{int} \) increases rapidly to 3 nW and \( \Delta f \) has a maxi-
minimum of 25 MHz. This indicates the onset of spin-transfer
force induced vortex oscillations ("STT-VO"). Then, we
observe a transient region\(^{10}\) for 3.5 mA < \Idc < 4.5 mA, in
which \( f \) increases rapidly and \( \Delta f \) starts to decrease. Finally,
able \Idc < 4.5 mA, the frequency \( f \) (Fig. 1(a)) follows a
quasi-linearly behavior and the corresponding linewidth \( \Delta f \)
(Fig. 1(b)), reaches a minimum value (≈ 1 MHz) that
remains unchanged with increasing \Idc. The integrated power
\( P_{int} \) increases up to a value of 25 nW for the maximum \Idc
(Fig. 1(c)). This behavior corresponds to an increase of the
radius of the vortex-core oscillation. Interestingly, the
linear coefficient \( N \) is negligible for the whole current range.
Note that, the maximum integrated power of all measured
samples is 48 nW, which is, to our knowledge, the largest
power value obtained with spin transfer nano-oscillators
with \( \Delta f \) of the order of 1 MHz.

Hereafter, we investigate the temperature dependence of the
microwave characteristics in the ("STT-VO") regime. In
Fig. 2(a), we focus on \( f \) and \( P_{int} \) for the case of
\H_{perp} = 5.5 kG
at four different temperatures (20–100–200–300 K). We see
that for both \Idc = 5 and 7 mA, \( f \) decreases by less than
5% between 20 K and 300 K. We have checked that this
reduction is related to the decrease in temperature of the satu-
ration magnetization \( M_s \). In order to get this latter depend-
ance,\(^{16}\) we have fitted the evolution of \( f \) vs \H_{perp} at each
temperature (not shown) using the analytical expression
valid for the gyrotropic motion of the vortex core:
\f(H_{perp}) = f(0)(1 + H_{perp}/4\pi M_s). \)
In Fig. 2(b), we plot \( P_{int} \) vs
T for the same current values. For both \Idc = 5 mA and
Idc = 7 mA, the integrated power \( P_{int} \) decreases about 70%
between 20 K and 300 K. \( P_{int} \) is expressed by the formula,
\\[ P_{int} = \frac{Z_0}{Z_0 + R} \left( \frac{\Delta R_{MR}}{\Delta f} \right)^2, \]
where \( R \) is the sample resistance and \( Z_0 \) is the circuit load
(here 50 Ω). For the case of vortex core gyration, the ampli-
tude of resistance oscillations is written as
\( \Delta R_{MR} = (\Delta M/M_s)\Delta R_{MR}/\Delta f \)
with \( \Delta R_{MR} \), the resistance variation between parallel and
antiparallel configuration. The amplitude of magnetization oscillations is proportional to the radius of the vortex
core \( \Delta M/M_s \propto \rho/D \), where \( D \) is the pillar diameter.\(^{17}\)
The temperature dependence of several parameters, i.e., \( R \),
saturation magnetizations of both SAF and free layer, \( \Delta R_{MR} \)
and both frequency and radius of the oscillation, make dif-
cult the detail explanation of the reduction of \( P_{int} \) with tem-
perature. However, a reasonable estimation (60%) can be
obtained by simply considering the temperature dependence of
both \( \Delta R_{MR} \) and \( M_{s,c} \).

In Fig. 3(a), we display the temperature dependence of \( \Delta f \)
at several current values, all above the threshold current. At
each temperature and for each \Idc, the plotted value of \( \Delta f \)
corresponds to the average value of the peak linewidth measured
in the \H_{perp} region for which the integrated power \( P_{int} \) is maxi-
imum (see Fig. 2 in Ref. 7). The most striking result is that we
measure a constant bottom limit value \( \Delta f \approx 700 \text{kHz} \) at low
temperature, that is moreover almost independent of \Idc. Nota-
\(\\text{bly, it excludes the Joule heating as possible origin of this lin-
ewidth limit. This is in contradiction to the expectation that in
our weakly nonlinear vortex based oscillators, the linewidth
should depend linearly on temperature. Indeed we recover this
linear dependence of \( \Delta f \) vs \( T \) above 100 K for \Idc = 5 mA
and at higher temperature for higher \Idc. A similar behavior,
\(\text{already observed in metallic nanocontact devices,}\)
was never measured in TMR structures, due to their intrinsic larger
noise.\(^{5}\) At \( T = 300 \text{K} \), the minimum \( \Delta f = 1 \text{MHz} \) measured for
\Idc = 7 mA is indeed about twice larger than the one that can
be estimated from Eq. (1). This difference, as well as the limit
value of \( \Delta f \) found in the temperature dependence, indicates
that a new source of linewidth has to be considered in case of
our vortex based oscillators. In order to get insights, we com-
pare the background noise \( P_n \) at different \Idc and \( T \) (Fig. 3(b)).
\( P_n \) was extracted for each spectra in the range between 100
and 1200 MHz. In the subcritical current regime, \( P_n \) strongly
depends on temperature and is constant while \Idc increases.
This behavior is expected in this regime of thermally activated
vortex oscillations. On the contrary, above the threshold cur-
rent, we first observe an intermediate regime in which \( P_n \)
decreases very fast to a bottom limit value, reached at the
same \Idc for all temperatures. Then, for \Idc > 4.6 mA, the back-
ground noise is constant. Indeed, this behavior is very similar
to the one observed for \( \Delta f \) as function of \Idc, shown in Fig.
1(b). Interestingly, note that \( P_n \), in this over-critical regime,
is independent on temperature. These results clarify that, unlike
the case of spin-transfer excitation of uniform magnetization
in MTJ,\(^{5}\) the spin transfer torque is not the main source of the
linewidth through the nonlinearity of the frequency in our
STVO. Furthermore, the comparison of our quality factor
of local inhomogeneities of the effective field that would be seen by the vortex core during its motion as a fluctuating field. These possible explanations need further investigations through micromagnetic simulations and time-domain measurements.\textsuperscript{20,21}

In conclusion, we find that, in the regime of large vortex trajectories, the nonlinear coefficient is much lower than in uniform magnetization. It explains why the peak linewidth is almost constant on the whole current range. We investigate the origin of the linewidth by measuring the temperature dependence of the rf signal. We find that by decreasing the temperature, the linewidth first linearly decreases as expected but then saturates and reaches a bottom limit value (about 700 kHz) independent on \( I_{sd} \). Thus, we conclude that both thermal effects and spin transfer nonlinearities cannot account for the observed results and an additional source of phase noise has to be invoked.

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The dependence of frequency \( \nu \) (a) and integrated power \( P_{int} \) (b) on temperature for \( I_{sd} = 5 \) and 7 mA.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{(Color online) The dependence of the linewidth \( \Delta \nu \) on temperature for \( I_{sd} = 5 \) and 7 mA. (b) Background noise \( P_{b} \) vs \( I_{sd} \) for 20 K, 100 K, 200 K, and 300 K.}
\end{figure}

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