Wireless communication between two magnetic tunnel junctions acting as oscillator and diode

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Magnetic tunnel junctions are nanoscale spintronic devices with microwave generation and detection capabilities. Here we use the rectification effect called "spin-diode" in a magnetic tunnel junction to wirelessly detect the microwave emission of another junction in the auto-oscillatory regime. We show that the rectified spin-diode voltage measured at the receiving junction end can be reconstructed from the independently measured auto-oscillation and spin diode spectra in each junction. Finally we develop an analytical model that accurately reproduces dynamical simulations and accounts for the experimentally observed features. These results will be useful to design circuits and chips based on spintronic nanodevices communicating through microwaves.

I. INTRODUCTION

The spin-transfer torque carried by a spin-polarized direct electric current $I_{dc}$ in magnetic tunnel junctions can induce magnetization auto-oscillations in the free magnetic layer. This process is fundamental in spin-torque nano-oscillators where magnetization dynamics are sustained and converted to voltage oscillations in the GHz range. Spin-torque nano-oscillators are promising as microwave emitters for future wireless applications due to their nanoscale dimensions, their large signal to noise ratio, and their ability to modulate and demodulate signals. When carried by a microwave current $I_{RF}(t) = I_{RF} \sin(\omega t)$, spin torque gives rise to the spin-diode effect. The spin-polarized microwave current excites an oscillating spin torque on the magnetization of the free layer, leading to resonant magnetization precessions and consequently to resistance oscillations of the junction $R(t)$. The oscillating resistance partly rectifies the current such that a dc voltage $V_{SD} = \langle I_{RF}(t) R(t) \rangle$ builds across the junction. Since it was measured for the first time, the spin diode effect was studied for energy harvesting, time-resolved measurements of resistance oscillations and microwave detection. Yet, the fundamental building block for future all-spintronic wireless communication network, consisting of a spin oscillator emitter and spin diode detector has not been demonstrated to date. The difficulty is to match their frequency so that the oscillator can influence the diode behaviour, as well as to analyze and understand the output signal at the detector.

In this letter we report the detection of the microwave signal emitted in free air by a first magnetic tunnel junction with the spin-diode effect in a second junction. We first measure the oscillator emission and the spin diode rectification separately. We then make the two junctions communicate through microwave antennas and study the evolution of the spin-diode signal as a function of the dc current in the oscillator as well as the amplification gain in the line. We show that we can accurately reconstruct and understand the measured spin-diode signal by combining the microwave signals from the two independent junctions. Finally we develop an analytical model that perfectly reproduces dynamical simulations and accurately accounts for the experimentally measured features.

II. EXPERIMENTAL SETUP AND DEVICE PARAMETERS

Both the spin-torque oscillator and the spin-torque diode used in this experiment are nano-pillars composed of a 1.8 nm thick CoFeB layer whose magnetization is pinned by an underlying synthetic antiferromagnet, 1 nm thick MgO insulating barrier and 7 nm thick NiFe free magnetic layer whose ground state is a magnetic vortex. The junction used as a detector is resonantly excited by an RF current, which means that it will respond in a frequency range around its resonant frequency. The junction used as an emitter is biased with a direct current to induce auto-oscillation. In the case of vortex oscillators, due to the Oersted field, the frequency of the junction increases strongly compared to the base resonant frequency when it is biased with a direct current. This means that the resonant frequency of the emitter junction should be lower than the frequency of the diode junction so that their operation frequencies match. The resonant frequency of vortex oscillators depends inversely on the diameter of the junction. Here we use a diameter of 400 nm for the oscillator junction and a diameter of 250 nm for the diode junction. We furthermore independently tune the magnetic field applied to each junction to modify their individual frequencies.

The schematic of the experimental setup is shown in Figure 1(a). We begin by measuring the spin-torque oscillator alone. We apply a magnetic field $\vec{H}$ perpendicular to the magnetic stack to cant the magnetization of the pinned reference layer with respect to that of the free layer, which is important to create a spin torque with the proper symmetry to induce sustained vortex gyration. When the injected direct current $I_{dc}$ is larger than a critical threshold value $I^{th}$, the spin torque is sufficient to induce oscillations of the vortex core. We measure the resulting microwave voltage across the junction $V(t)$ with a Power Spectrum Analyser. The frequency and
FIG. 1. (a) Schematic of the measurement setup. Both the spin-torque nano-oscillator and spin-torque diode are magnetic tunnel junctions, composed of two ferromagnets separated by a thin non-magnetic layer (yellow). The magnetization of the bottom ferromagnet (grey) is pinned, whereas that of the top one (blue) is free. (b) Frequency (points) and power (line) of the oscillator after amplification as a function of current $I_{dc}$ extracted from the measured power spectra for two different oscillator fields $H = 5200$ Oe (red) and $H = 5000$ Oe (blue). (c) Measured rectified spin diode voltage at $H_{\text{diode}} = 3000$ Oe as a function of the microwave source frequency for different color coded source powers.

FIG. 2. Measured spin diode voltage as a function of the current in the oscillator for different oscillator fields $H$. Dashed lines show the voltage reconstructed from the oscillator amplitude at a given current (shown for $H = 5200$ Oe and $H = 5000$ Oe in Figure 1(b)) and spin diode voltage at a given frequency (Figure 1(c)).

III. RESULTS

We first study the spin-torque diode alone by applying to the second junction a microwave current $I_{RF}(t)$. The experiment is performed in the presence of a perpendicular magnetic field $H_{\text{diode}} = 3000$ Oe chosen to bring the spin diode resonance within the frequency range of the oscillator. The voltage measured as a function of the microwave frequency is shown in Figure 1(c) for different microwave source powers. The shape of the power spectra is mainly anti-Lorentzian, corresponding to a dominant contribution of the field-like torque terms. Due to the oscillator nonlinearity, the resonance frequency increases with increasing power.

In a second step, we use the spin-torque diode effect in the second magnetic tunnel junction to detect the oscillator emission from the first junction. The amplified oscillator voltage is injected into a wireless transceiver RF antenna with mean attenuation of 7 dB in the diode resonance range and lower and higher cutoff frequencies of respectively 240 and 360 MHz. The signal is received by another identical antenna that is placed as close as possible to the first one in order to minimize the losses. The receiver antenna converts it to a microwave current that is injected into the second junction that is injected into the second junction, resulting in the spin-diode voltage plotted in Figure 2. We first focus on the curve at $H = 5200$ Oe showing the evolution of this signal as a function of the current in the oscillator. For currents below 9 mA, the curve is confined close to zero because the power of the oscillator is too small and its linewidth is too large to induce a large spin-diode signal. Above 9 mA, the power increases, the linewidth decreases and a spin-diode signal appears. The oscillator frequency increases with the input current, and spans from 280 to 305 MHz across the spin diode resonance. The resulting spin-diode voltage has an anti-Lorentzian-like shape as a function of the oscillator current similar to the measurements of Fig. 1(c). However this shape
is distorted because the power emitted by the oscillator is not constant. It increases with current, so that the absolute value of the spin-diode voltage is enhanced at large currents compared to Fig. 1(c). As expected, the detected signal amplitude increases with the gain. Furthermore, the curve shifts with amplification, which comes from the non-linear dynamical equation

\[
\frac{dc}{dt} = (-i\omega + \Gamma_+)c^2c + F_ee^{-i(\omega_+ t)},
\]

(1)

where \(c = \sqrt{\rho}e^{i\phi}\) is the complex amplitude of the oscillations in the considered junction, \(p\) is the normalized oscillation power, \(\phi\) is its phase and \(\Gamma_+\) is the net damping rate. \(F_e\) accounts for the microwave force exerted on the diode. It is set to zero in the oscillator junction. We assume that the damping rate depends on power only to the first order:

\[
\Gamma_+(p) = \Gamma_G(1 + Qp),
\]

(2)

where \(\Gamma_G = \omega_0\alpha_G\), \(\alpha_G\) is the Gilbert damping and \(Q\) accounts for non-linearity in damping and magnetization confinement.

We first derive the spin-diode signal from these equations. We find that for a vortex oscillator, the spin diode voltage is given by (see Appendix I for details):

\[
V_{SD} \propto p_d(\delta - \omega_0^2N_ap_d),
\]

(3)
where $p_d$ is the normalized oscillation power in the diode, $N_d$ the non-linear frequency shift of the diode, $\omega_d^0$ the diode resonance frequency and $\delta = \omega_c - \omega_d^0$ is the frequency difference between the source and the diode.

For the spin-diode junction, the exact stationary solution of Eq. (1) for the oscillation power is given by (see Appendix I for details)

$$(Q_d^2 \Gamma_G + (\omega_d^0)^2 N_d^2)p_d^3 + 2(Q_d \Gamma_G - \omega_d^0 N_d \delta)p_d^2 + (\Gamma_G + \delta^2)p_d = F_e^2.$$  

(4)

**TABLE I.** Table of parameters used in the simulations. The index osc refers to the oscillator, and $d$ to the diode.

| Parameter  | Value          |
|------------|----------------|
| $\alpha_d = \alpha_{osc}$ | 0.02          |
| $N_d = N_{osc}$ | 0.5           |
| $Q_d = Q_{osc}$ | 2             |
| $\omega_d^0$ | $2 \pi \times 290$ MHz |
| $\omega_{osc}^0$ | $2 \pi \times 280$ MHz |

We plot in Figure 3(a) in dashed lines the spin diode voltage $V_{SD}$ calculated from Eq. (4) as a function of microwave source frequency for different external drive forces $F_e$. We superimpose in full lines the numerical solution directly extracted from Eq. (1) using a fourth order Runge-Kutta method. The parameters that we used are given in Table I. Note that $c$ being a dimensionless amplitude, the driving force $F_e$ is homogeneous to a frequency. Figure 3(a) shows that the agreement between numerical and analytical solutions for the spin-diode signal is excellent. Furthermore, the experimental trends in Figure 1(c) are well reproduced: the shape of the spin-diode signal is anti-Lorentzian, its amplitude increases and the resonant frequency shifts with increasing power.

Next, we simulate the spin diode voltage as a function of the oscillator current for different amplification factors in Figure 4(b). The oscillator Gilbert damping $\alpha_{osc}$ and nonlinear coefficients for frequency $N_{osc}$ and damping $Q_{osc}$ are the same as the spin diode. The normalized oscillator power can be calculated from Eq. (1) at steady state with $F_e = 0$,

$$p_{osc} = \frac{1}{\xi + Q_{osc}} \text{ if } \xi > 1$$
$$p_{osc} = 0 \text{ if } \xi \leq 1,$$

(5)

where $\xi = \frac{F_e}{p_e}$. We consider that the driving force $F_e$ on the diode is proportional to the amplitude of the spin-torque oscillator

$$F_e = A \sqrt{p_{osc}},$$

(6)

where $A$ is a factor that depends on the overall amplification gain in the line and the spin-transfer torque efficiency.

We observe in Figure 4(b) a behavior that is qualitatively similar to the measurements. As expected, we observe the frequency shift due to the diode nonlinearity and diode voltage of larger amplitude for larger currents due to the oscillator power dependence on current. Our calculation does not take into account the bias-dependence of the Tunnel Magneto-Resistance in the oscillator, which explains why the spin-diode signal is larger at high currents in the predictions compared to the experiments. In the future, quantitative agreements can be obtained if necessary by refining the model to take into account experimental details such as amplification losses in the cables and line, bias dependence of Tunnel Magneto-Resistance and spin-transfer torque, as well as accounting for torques with different symmetries and strengths in Eq. (1).

In conclusion, we have wirelessly connected a spin-torque nano-oscillator to a spin-torque diode, and demonstrated that the spin-diode can detect the spin-oscillator microwave emission. We have reconstructed the measured rectified voltage from the independently measured auto-oscillation and spin diode spectra and shown that we can predict well the measurement result. We have developed and analytical model that perfectly reproduces dynamical simulations and accounts for experimental trends. Our work paves the road towards realization of all-spintronic communication networks wirelessly connecting magnetic tunnel junction-based RF oscillators and diodes.

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V. APPENDIX I

The universal model for magnetization dynamics under the influence of DC and AC signals is given by Eq. (1). This complex equation can be rewritten as two real equations describing the power $p = |e|^2$ and the phase $\phi = \arg(e)$ of the junction.

$$\frac{dp}{dt} = -2\Gamma_+(p)p + 2\sqrt{p}F_e \cos(\phi + \omega_e t - \psi_e)$$

(7)

$$\frac{d\phi}{dt} = -\omega(p) - \frac{F_e}{\sqrt{p}} \sin(\phi + \omega_e t - \psi_e).$$

(8)

We concentrate here on the case of the diode, which only receives an AC input. We introduce the phase difference between the harmonic signal and the diode $\Phi = \phi + \omega_e t - \psi_e$, such that using Eq. (8) we find

$$\frac{d\Phi}{dt} = \delta - \omega_d^0 N_d p_d - \frac{F_e}{\sqrt{p_d}} \sin(\Phi),$$

(9)

where $\delta = \omega_c - \omega_d^0$ is the frequency difference between the oscillator and the diode resonance. The spin diode being a driven resonance phenomenon, we can consider that in steady state the phase difference between the diode and the harmonic signal is constant over time $\frac{d\Phi}{dt} = 0$, leading to

$$\Phi = \arcsin \left( \frac{\sqrt{p_d}(\delta - \omega_d^0 N_d p_d)}{F_e} \right).$$

(10)

Since we measure the spin-diode voltage over a time much larger (several ms) than the period of oscillations (several ns), we consider only the stationary regime $\frac{dp_d}{dt} = 0$. 


Then Eq. (7) yields $\cos \Phi = \sqrt{p C} (\sin(\omega t + \psi_c))$ and using Eq. (10) and $\cos(\arcsin x) = \sqrt{1 - x^2}$, we obtain the exact diode oscillation power Eq. (11). The spin diode voltage is given by

$$V_{SD} = \langle I_{RF}(t) R(t) \rangle = I_{RF} \cos(-\omega_e t + \psi_c) R_{P \to AP} \sqrt{p d} \cos(\theta),$$

(11)

where $R_{P \to AP}$ is the resistance difference between the fully parallel state and the fully anti-parallel state, $\sqrt{p d}$ is the amplitude of oscillations in the diode and $\theta$ is the magnetoresistance oscillation phase. The force $F_c$ is proportional to the microwave amplitude $I_{RF}$. For a vortex magnetic tunnel junction, the phase of magnetoresistance oscillation is in phase quadrature with the phase of the vortex oscillation $\phi = \theta + C\pi/2$, where $C$ is the chirality of the vortex, such that

$$V_{SD} \propto \langle F_c \sqrt{p d} C \cos(-\omega_e t + \psi_c) \sin(\phi) \rangle = F_c \sqrt{p d} C \langle \cos(\theta) \sin(\phi) \rangle/2.$$

(12)

The first term averages out over time leading to

$$V_{SD} \propto C F_c \sqrt{p d} \sin \Phi.$$

(13)

Finally using Eq. (10) et Eq. (14) we find Eq. (3).

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