Nanocontact size dependence of the properties of vortex-based spin torque oscillators

R. M. Otxoa^{*,1,2}, M. Manfrini^{3,4}, T. Devolder^{1,2}, J.-V. Kim^{1,2}, W. van Roy³, L. Lagae^{3,4}, and C. Chappert^{1,2}

¹Institut d'Electronique Fondamentale, UMR CNRS 8622, 91405 Orsay cedex, France

²Universite Paris-Sud, UMR 8622, 91405 Orsay, France

³IMEC, Kapeldreef 75, 3001 Leuven, Belgium

⁴Laboratorium voor Vaste-Stoffysica en Magnetisme, K. U. Leuven, Celestijnenlaan 200 D, 3001 Leuven, Belgium

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* Corresponding author: e-mail ruben.otxo@u-psud.fr, Phone: (+33) 1 69 15 40 13, Fax : (+33) 1 69 15 78 41

We study the frequency, linewidth, and power of spin torque driven vortex oscillators, based on a nanocontacted spin-valve (SV). The oscillation frequency strongly decreases with the contact size, and increases with the current. The power delivered by the oscillator is not quadratic with the current,

in contrast with the behavior expected from the rigid vortex model (RVM). The linewidth is almost independent of the current at low current and does not strongly depend on the nanocontact size. We compare our findings with the outcomes of the RVM.

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1 Introduction Magnetic vortices have recently received much attention [1–3] in the field of micromagnetism since it was discovered that they are fundamental states on the microscopic and nanoscopic scale which have potential applications in information storage and spintronic devices. The spin transfer phenomenon [1], where a polarized current transfers angular momentum to the magnetic moments of a ferromagnetic material provides a new method to manipulate the magnetization without the application of any external field. In the system that we present here instead of taking advantage of the confined magnetic structures we use a typical magnetic system called spin-valve (SV) with a metallic nanocontact on the top of this magnetoresistive structure. The current is injected into the magnetic multilayer which are normally composed by ferromagnetic layers separated by a non-magnetic layer. In this kind of system, large current densities flow through the magnetic multilayer structure which can lead to large spin torque effects. Under certain conditions the Oersted–Ampere field associated with the current can nucleate a vortex [4] which will be carried into a steady state of motion around the point contact (PC) [2, 5]. These self-sustained oscillations are generated in the 50–500 MHz range.

It has been experimentally demonstrated recently that vortex oscillators have characters that make them very interesting for potential applications such as its high quality factor, agility [6], and that the gyrotropic motion is controllable without the application of additional large magnetic fields [4, 7].

In this paper, we present an experimental study of the PC size dependence of the oscillation frequency in a magnetic nanocontact system. Also other characteristic features like linewidth and power will be discussed. Notice that these experiments were made under zero in plane and perpendicular fields, which means there is no vortex in the initial state. In the last section we will compare the latest theories presented to date and our experimental results.

2 Samples and experimental setup The experimental system studied is a metallic nano-PC fabricated on top of our SV. We use nanocontacts with nominal radii of 40, 50, 60, 80 nm most of them showing vortex oscillations. The nominal size can be quite different from the physical or “real” size of the PC, therefore this will be discussed in Section 3. The composition of the SV is the following: Ni₈₀Fe₂₀(3)IrMn(6)/Co₉₀Fe₁₀(4.5)/Cu(3.5)/Ni₈₀Fe₂₀(4)/Pt(3). The number in parentheses denote the layer thicknesses in nanometers. In this structure (see Fig. 1) the layer which

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Figure 1 (online colour at: www.pss-b.com) Frequency *versus* current for different nano-contact radius of 40 (top green curve), 50, 60, 80 (bottom gray curve) nm. Dots represent experimental data. Throughout all of this paper we consider the same code of colors for each PC size.

plays the role of the free layer (FL) is $\text{Ni}_{80}\text{Fe}_{20}$ (4) while CoFe (4.5) layer is exchange biased by the IrMn (6), an antiferromagnet that serves as a pinned layer (PL) for the giant magnetoresistance (GMR) variations. Details in fabrication process have been given elsewhere [5].

The device was measured at room temperature and the magnetization dynamics was detected by electrical measurements via the GMR effect. The experimental procedure to study the dependence between oscillation frequency and the applied current have been described elsewhere [5].

3 Results

3.1 Nucleation current *versus* PC size Starting from zero current, it is necessary to apply a threshold current amplitude to nucleate the vortex [5] (see Fig. 1). The threshold current usually called nucleation current I_{nuc} increases with the PC size, being 25 mA for smallest PC and 42 mA for the biggest one (see Fig. 1). It is possible to maintain this self-sustained oscillations till values in the order of 6–10 mA [4]. Once the vortex is nucleated, the frequency depends quasi-linearly with the current (see Fig. 1). We focus on this regime, where the vortex shows a dynamical behavior.

3.2 Estimate of real PC size The aim now is to extract the physical size of the PC and find a general trend between frequency and “real” PC. To do that we used two different methods. In the first one, we take into account that the total circuit resistance is the sum of the resistance of the electrodes R_{elec} plus a contribution due to the relative magnetic orientation between the PL and FL which we call ΔR ; GMR represents the GMR ratio which is extracted from

the fit [see Eq. (1)]:

$$R_t = R_{\text{elec}} + \frac{\Delta R}{\text{GMR}}. \quad (1)$$

In the second method, we use the fact that it is possible to find a relation between the nucleation current and the total resistance of our device:

$$R_t = R_{\text{elec}} + \frac{K}{I_{\text{nuc}}}. \quad (2)$$

In the first method, depending on the size of the PC we obtain different values for the total resistance R_t and ΔR which allow us to get from the slope R_t *versus* ΔR the resistance of the electrodes, which is independent on the size of the PC. Typically the values for ΔR are 25 m Ω for smallest and 17 m Ω for the biggest PC. The value for R_{elec} is $5.8 \pm 0.3 \Omega$. The value of GMR extracted is 1.1%. Once this is done we can directly obtain the resistance of the PC. $R_{\text{pc}} = R_t - R_{\text{elec}} = 1.2\text{--}2.3 \Omega$. In the second method we use the same procedure, extract the resistance of PC from the fit. Considering the above assumptions together with the fact that the resistance of the PC is directly proportional to the inverse of the square of the PC radius, $R_{\text{pc}} = K/a_{\text{pc}}^2$, it is possible to extract the real values of the different PC sizes. To do that, we do the strong assumption that the nominal radius of the PC of 100 nm coincides with its real radius size. This allows us to directly deduce the physical radius of each of the other points of contact and be able to get as close as possible to real relation between the slope and radius of the contact point. In Fig. 2 is represented slope *versus* a_{pc}^{-2} taking into account the real PC size. We must say that as can be seen in

Figure 2 (online colour at: www.pss-b.com) Representation of slope *versus* a_{pc}^{-2} by two different methods. (a) is obtained using ΔR and (b) is obtained using $1/I_{nuc}$.

both Fig. 2(a) and (b) the real PC's sizes do not change too much for each method used, which means that the assumption about how to extract the physical sizes was consistent between both. The fabricated devices have a physical size slightly bigger than intended, with a radius size offset of 15 nm. We find a relation between oscillation frequency of the vortex around the PC and the PC radius:

$$f \propto \frac{1}{a_{pc}^2}. \quad (3)$$

3.3 Frequency versus PC size In Fig. 3, we study the slope (df/dI) *versus* the nominal PC size, we see a strong decreasing in the slope *versus* the PC size, which means that the PC size plays an important role in the oscillation frequency of the vortex.

3.4 Power dependence with PC size The power delivered to the measurement circuit comes from the vortex orbital motion in the PC region. The vortex motion gives rise a time-varying change in the magnetoresistance (ΔR_{dyn}). It is possible to estimate the radius of the vortex orbit during its

Figure 3 (online colour at: www.pss-b.com) Dependence of frequency *versus* current slope with the nanocontact size.

motion. The procedure is the following. If the sample resistance varies like $(\Delta R_{dyn}/2) \cdot \sin(\omega t)$ and the device is submitted to an I_{dc} current while connected in series with Z_{load} at its both electrodes, it will deliver to the measurement circuit the following power:

$$P = \frac{Z_{load} \cdot \Delta R_{dyn}^2 \cdot I_{dc}^2}{8 \cdot (Z_{load} + Z_{out})^2}, \quad (4)$$

where $Z_{load} = 50 \Omega$ and $Z_{out} = Z_{load} + R_{dut} = 55.8 \Omega$ which is the sum of 50Ω series resistance and the resistance of the device including its electrodes. Considering the “Rigid vortex model” (RVM) [8] in which it is assumed that the vortex can be considered as a rigid object (even when it is moving) without internal degrees of freedom, it is possible to express analytically the value of ΔR_{dyn} in terms of the radius of the orbit that the vortex follows, simply solving the integral of Eq. (5):

$$\begin{aligned} \Delta R_{dyn}(r_{vx}) &= \frac{R_{pc} \cdot GMR}{2} \iint_{PC} \mathbf{m}(r)_{fl} \cdot \mathbf{m}(r)_{fx} \cdot d\mathbf{r} \\ &= \frac{R_{pc} \cdot GMR}{2} \iint_{PC} \frac{(r-R \cdot \cos(\phi)) d\mathbf{r} d\phi}{\sqrt{R^2 + r^2 - 2 \cdot r \cdot R \cdot \cos(\phi)}}. \end{aligned} \quad (5)$$

To simplify the calculations, it is assumed that the magnetization of the PL remains static and plays no role in the dynamics of the vortex which relies in the FL. $\mathbf{m}(r)_{fl}$ and $\mathbf{m}(r)_{fx}$ refer to magnetization of the FL and fixed layer respectively. $\mathbf{r}$ and $\mathbf{R}$ represent position vectors in polar coordinates of the point of study and the vortex core position, respectively.

In Fig. 4, R_{orbit}/a_{pc} represents the ratio between the orbit radius of the vortex and the PC radius. It is easy to see that when the vortex is far away from the PC we get $\Delta R_{dyn} = R_{pc} \cdot GMR$. This would mean that the vortex has been expelled and now our magnetic layers relies uniform magnetized (without vortex).

From the power *versus* current for different PC sizes we see an interesting trend for each PC size. After a value of current we can see an important decreases in the power. This is something unexpected but can be explained by at least two different scenarios. First one, contrary with the RVM [8] predicts, the orbit radius could be dependent with current. In this scenario the decay process of the orbit trajectory of the vortex behind the PC region could give rise a decreases in ΔR_{dyn} as can be seen in Fig. 4. One way to check this possible explanation is to apply perpendicular field and see whether the ΔR_{dyn} changes or not. As we know the confining potential created by the current would be reduced by this perpendicular fields, which would lead to a variation in the orbit of the vortex.

Another explanation for the decrease in the power could come from the fact that the PL is not completely pinned and is distorted by the presence of the current. This would make a competition between the uniform field from the layer and the Oersted field generated by the current. This could be tested

Figure 4 (online colour at: www.pss-b.com) Figure on the left represents experimental data of $\Delta R_{\text{dyn}} = R_{\text{pc}} \cdot \text{GMR}$ versus I_{dc} and right figure represents numerical solution of the Eq. (5) for $\Delta R_{\text{dyn}} = R_{\text{pc}} \cdot \text{GMR}$ as function of the position of the vortex in the layer in which it relies, taking the reference system in the center of the PC.

Figure 5 (online colour at: www.pss-b.com) Linewidth versus current for different PC sizes. Inset figure represents the linewidth versus current for the PC $a_{\text{pc}}^{\text{nominal}} = 60$ nm.

by applying small fields along the in-plane direction watching whether there is a variation again in the power spectra.

3.5 Linewidth versus current Another important feature of the vortex motion is related to the linewidth. As can be seen in Fig. 5, very low linewidths are reached for every PC when we are in the range of 10–25 mA. As can be seen in the inset figure of Fig. 5, the lowest linewidth reached is 1.2 MHz which corresponds to a PC size of 60 nm nominal

radius. In the RVM Δf is directly proportional to the inverse of the square of the orbit radius:

$$\Delta f \propto \frac{1}{R_0^2}. \quad (6)$$

We show in Fig. 5 that when the current reaches 25 mA, suddenly the linewidth increases, this means (following the RVM approach) that the orbit of the vortex has decreased substantially. It is possible to see in Fig. 4 that also there is a transition regime around (24–25) mA from which ΔR_{dyn} suffers an important decay. This would give more strength on the idea of the reduction of the radius trajectory orbit of the vortex when we increase enough the current.

4 Discussion and concluding remarks Let us summarize our experimental results, and compare them to the prediction of the RVM. Nucleation current is consistent with a current density-based mechanism. Frequency slope decreases with PC size, in contrast to predictions done from the RVM that conclude $df/da_{\text{pc}} = 0$. Power versus current curve is consistent with the vortex orbit R_0 , being the most extended near 12–16 mA. This corresponds to a shallow linewidth minimum, consistent with the predictions that Δf decreases with R_0 . For 40 and 50 nm we can certify that at low currents 10–20 mA the vortex orbits outside of the PC. At large current, there is a systematic drastic increase of linewidth whose origin is unclear. Our results call for a more elaborate theory of vortex based dynamics taking into account the real geometry.

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