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Spintronic Nanoscillators for Unconventional Circuits

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Abstract—Spintronic nanodevices – which exploit both the magnetic and electric properties of electrons – are a major breakthrough for nanoelectronics. The flagship device of spintronics, the magnetic tunnel junction, naturally provides a binary memristive device with outstanding endurance, high speed and low energy consumption. Interestingly, relying on the same physics as their use as memristive devices, magnetic tunnel junctions may also be used as a type of voltage controlled oscillators: at a given voltage, oscillations in their electrical resistance and currents can be observed. Depending on the tuning of the devices geometrical and magnetic properties, the oscillations can be slow and stochastic, or fast and quasi-harmonic. In this work, we introduce experimentally validated models for these two regimes. We discuss the synchronization potential of these oscillators, as well as their possible use in unconventional circuits. Prospects for bioinspired systems are given. This work raises important questions regarding the use of nanooscillators in circuits, which we discuss in conclusion.

I. INTRODUCTION

Spin electronics, or spintronics, is a major breakthrough of micro- and nano-electronics, highlighted by the Nobel price awarded to Albert Fert and Peter Grünberg in 2007. A spintronic device function is using not only the charge, but also the intrinsic magnetic moment, or spin, of electrons. The flagship device of spintronics is the spin torque magnetic tunnel junction, which can be viewed as a binary memristive device, with multiple advantages: it is compact and scalable, its endurance is outstanding, switching is fast and low-energy [1]. These properties make this device an appealing candidate for standalone and embedded non-volatile memory applications, and multiple industries are now developing spin torque magnetic random access memory (ST-MRAM) exploiting them. A significant drawback is the stochastic nature of switching of these devices [1], which needs to be addressed through adapted circuit techniques. These stochastic effects could also be exploited, reinterpreting spin torque magnetic tunnel junctions as artificial synapses [2], [3].

However, and quite strikingly, through the exploitation of the same physics as their use for memristive devices, spin torque magnetic tunnel junctions can also behave as oscillators [4], [5]. These oscillations are voltage-controlled and are exhibited in the electrical resistance of the device, and observed in two different regimes: slow stochastic oscillations, or fast (microwave) deterministic oscillations. The properties of the oscillators can be designed through materials properties and device sizing, as well as through a magnetic field. In this work,

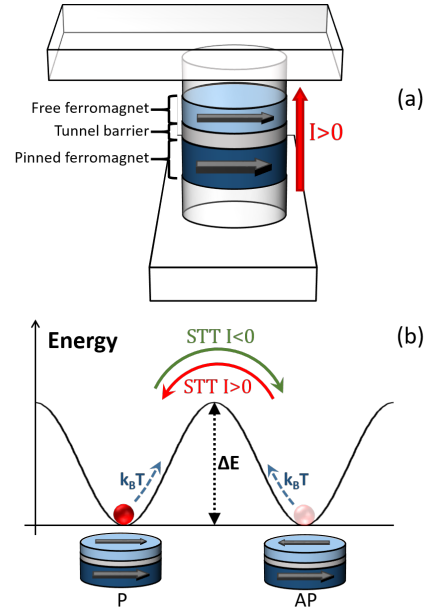


Fig. 1. (a) Simplified illustration of a typical magnetic tunnel junction. (b) Illustration of the energy barrier of a magnetic tunnel junction, with two stable states and the influence of electrical current through spin transfer torque (STT).

we review these two regimes and propose experimentally validated models that can be used for circuit theory. We discuss to what extent these oscillators can be controlled, as well as their synchronization properties. We propose examples of prospects for bioinspired circuits.

II. STOCHASTIC NANOOSCILLATORS BASED ON SUPERPARAMAGNETIC TUNNEL JUNCTIONS

Spin torque magnetic tunnel junctions are composed of several layers of materials: two magnetic layers separated by an oxide layer (Fig. 1(a)). One of the magnetic layer has fixed magnetization, while the other layer, the free layer, can have its magnetization switched parallel or anti-parallel to the fixed layer. These orientations, P and AP, constitute the two stable states of the magnetic tunnel junction and correspond to different electrical resistance due to the tunnel magnetoresistance effect. By applying a negative or a positive current to the junction, through the physical spin transfer torque effect, the state of the junction can be switched (Fig. 1(b)). This

effectively makes spin torque magnetic tunnel junctions binary memristive devices.

The stability of the two states of spin torque magnetic tunnel junctions used as memristive devices is determined by their sizing and their materials properties [1]. When used as non-volatile memories, those properties are chosen for high stability (*i.e.* retention higher than 10 years). However, it is also possible to intentionally design spin torque magnetic tunnel junctions for low stability. In this case, the junction is called “superparamagnetic” and naturally switches between its two states due to thermal noise, following a Poisson process (Fig. 2) [5]–[7]. The “natural frequency” of such junctions, corresponding to their mean number of oscillations per unit of time, is:

$$F = \frac{1}{\langle \tau_{AP} \rangle + \langle \tau_P \rangle}, \quad (1)$$

where $\langle \tau_{AP/P} \rangle$ are the mean dwell times in the P and AP states. As switching is thermal, it is slow. In Fig. 2, the device switches at kHz rates. It can go in the range of MHz frequencies.

The device behavior can effectively be modeled using a Arrhenius-Neel two-state analysis, meaning that the device switches following a Poisson process. The switching rate is $1/\langle \tau_{AP} \rangle$ in AP state and $1/\langle \tau_P \rangle$ in P state. In other words, if the switching rate is constant, the probability to switch between times 0 and t is given by

$$P_{AP/P}(t) = 1 - \exp\left(-\frac{t}{\langle \tau_{AP/P} \rangle}\right), \quad (2)$$

The mean times $\langle \tau_{AP/P} \rangle$ are given by: $\langle \tau_{AP/P} \rangle = \tau_0 \exp\left(\frac{\Delta E}{k_B T}\right)$ where ΔE is an energy barrier separating the two states of the junction, τ_0 is called effective attempt time, T is the temperature, and k_B the Boltzmann constant.

The relative stability of the two states as well as switching speed can be strongly influenced by the application of an electrical current through the spin transfer torque effect. An external magnetic field can indeed modify the energy landscape. Through spin transfer torque effect, an electrical current also changes the stability of the states [8] - as illustrated in Fig. 2(a) [6], [9], [10]:

$$\langle \tau_{AP/P} \rangle = \tau_0 \exp\left(\frac{\Delta E}{k_B T} \left(1 \pm \frac{V}{V_c}\right) \left(1 \mp \frac{H - H_0}{H_k}\right)^n\right), \quad (3)$$

where V_c is the junction critical voltage, V is the bias seen by the junction, H is the magnetic field along the junction easy axis, H_k is its anisotropy and n is a real coefficient. H_0 is a residual field due to the fixed layer.

Although superparamagnetic junctions are extremely stochastic, they can exhibit very complex and interesting behaviors from a dynamic point of view. In particular, they exhibit a capability to synchronize to weak, subthreshold inputs [5], [7]. This form of synchronization, analogous to synchronization by stochastic resonance, exhibits surprising properties, as illustrated in Fig. 3. A subthreshold AC input, superimposed to white noise, is applied as a voltage to a

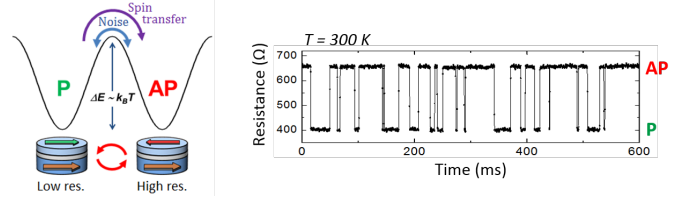


Fig. 2. Superparamagnetic tunnel junctions acting as stochastic oscillator: (a) schematic and (b) experimental measurement of resistance as function of time. Experimental details are given in [7].

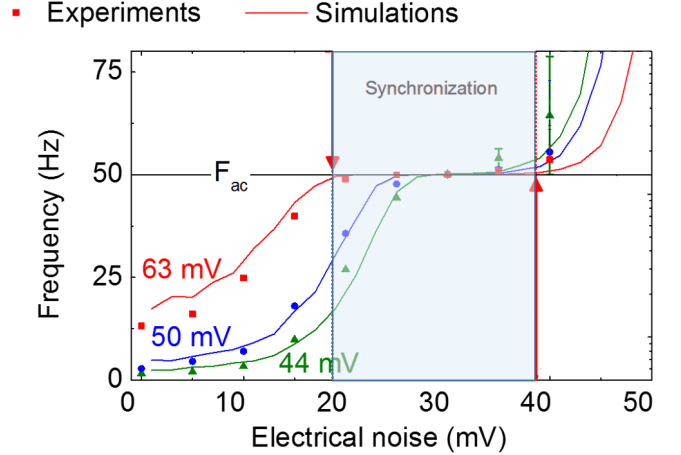


Fig. 3. Synchronization experiment applied to a stochastic oscillator. A subthreshold AC signal with noise is applied on a stochastic oscillator. Mean frequency of the oscillator as function of noise level and for different AC amplitudes. Experimental details are given in [7].

superparamagnetic junction. Fig. 3 plots experimental measurements of the mean frequency of the junction as function of noise intensity and for different AC amplitudes. At low noise, the junction is not synchronized to the junction. At higher noise, synchronization is observed, that was therefore *induced* by noise. At even higher noise, this synchronization is lost. This behavior is perfectly explained by modeling, as we can see in Fig. 3 that a model based on equations (1-3) perfectly reproduces the experimental results. Superparamagnetic tunnel junctions, under appropriate condition, can also synchronize with each other, as studied in depth in [11].

This behavior can offer highly promising prospects for unconventional circuits. As superparamagnetic tunnel junctions switch due to thermal noise, they have the potential to be used in circuits that consume very little energy (therefore harvesting some energy from thermal noise). Bioinspiration could provide a route as many schemes for computing (*e.g.* associative memories) rely on synchronization [12], and multiple works have suggested that biology operates with stochastic resonance in some contexts [13].

III. DETERMINISTIC SPINTRONIC NANOOSCILLATORS

Magnetic tunnel junctions can exhibit a very different type of oscillations. When appropriate conditions are met, the magnetization of a nanomagnet can precess, at frequencies

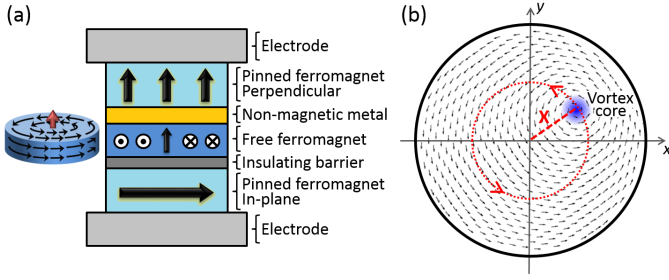


Fig. 4. (a) Schematic of a vortex oscillator. (b) Trajectory of the vortex during oscillation.

ranging between 100MHz to dozens of GHz . Many variations of such nanooscillators exist, here we focus on vortex based oscillators, introduced in Fig. 4 [4]. They consist in nanopillars composed of multiple magnetic and nonmagnetic layers, with a free magnetic layer in the middle and two pinned layers with orthogonal orientations. The bottom three layers implement a conventional magnetic tunnel junction. The remanent free layer magnetic state is called a vortex [14], where the magnetization curls in the free layer and goes perpendicular to the device in a center part (see Figure 4). The nanooscillator relies on a gyrotropic excitation, corresponding to a circular movement of the vortex [14] as seen in Fig. 4(b).

When an electrical current is applied to the junction, the different magnetic layers generate an effect on the vortex through spin-transfer [4]. If the current is above a certain threshold, the device demonstrates oscillations of its resistance: an oscillating voltage appears on the device. The frequency of the oscillators is determined by the applied current and is therefore tunable.

Different experimental physics studies have shown that this oscillation can be modeled by the Thiele equation [14], [15], where the whole device is modeled by the position of the vortex. Here, we present it with additional spin-transfer terms. $\mathbf{X} = \rho e^{i\chi}$ is the position of the vortex (see Figure 4(b)). The modified Thiele equation reads:

$$iG\dot{\mathbf{X}} + D(\rho)\dot{\mathbf{X}} + (k(\rho) - i\kappa_1 I)\mathbf{X} = \kappa_2 I + F_{noise}(t) \quad (4)$$

I is the electrical current, G is Gyrovector amplitude, D is the damping parameter, k is a confinement coefficient, $\rho = |\mathbf{X}|$, κ_1 , κ_2 are spin transfer efficiencies [16]. $F_{noise}(t)$ is a phenomenological stochastic force modeling fluctuations, based on fluctuation-dissipation theorem, as described in [17]. The model should also include an amplitude limitation through a maximum speed for the vortex as detailed in [16].

In parallel, the electrical resistance of the structure varies as:

$$R = R_{min} \left(1 + \frac{2}{3} C \text{TMR}_{\%} \frac{\text{Im}(\mathbf{X})}{r} \right) \quad (5)$$

R_{min} is the minimum resistance of the device, $\text{TMR}_{\%}$ its tunnel magnetoresistance, $C = \pm 1$, r is the radius of the device [16].

Fig. 5 shows a simple simulation of this equation, in a situation where the input current I is constant and equal to $260\mu\text{A}$. In Fig. 5(a), noise term $F_{noise}(t)$ is omitted, in

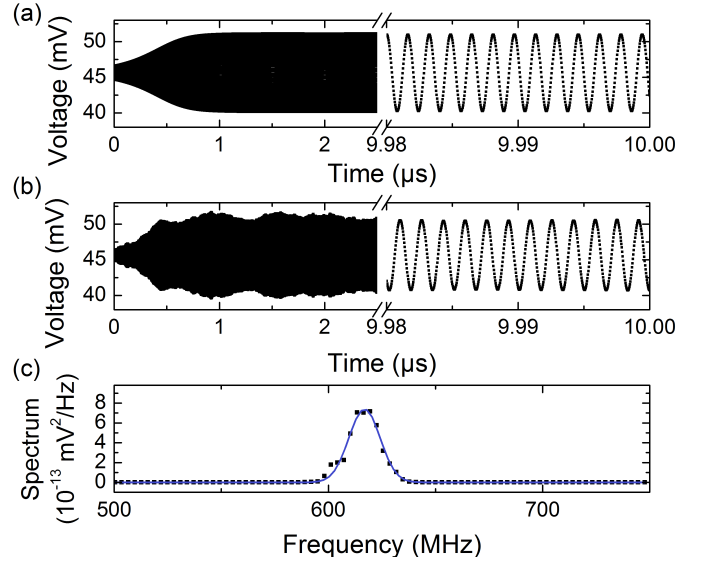


Fig. 5. Simulation of a vortex nanooscillator (a) without noise term and (b) with noise term. (c) spectrum of the simulation with noise.

Fig. 5(b) it is included. The frequency of the oscillation is 618MHz , which is consistent with the expected frequency for this particular device [14]. As seen in Figure 5(c), the noisy oscillator presents phase noise, corresponding to the linewidth of the peak that can be experimentally observed [4]. The linewidth extracted from simulations is 14.6MHz , while theory predicts 14.0MHz [17]. It should be noted that this relatively high degree of noise can be strongly reduced in other geometries [18].

Spin torque oscillators also possess a possibility to synchronize, to external sources, as well as to each other [19]. This possibility is exhaled by the nonlinearity of the oscillators, and leads multiple groups to investigate bioinspired computing schemes that rely on the synchronization of spin torque oscillators [20]–[23].

IV. CONCLUSION

Although magnetic tunnel junctions are currently mostly known as a form of binary memristive device, we have seen that can also exhibit extremely rich oscillatory behaviors. These oscillators rely on a technology very similar to ST-MRAM, which has demonstrated CMOS compatibility and very large scale integration potential. Their use may therefore be envisioned in systems with millions of oscillators. Two separate regimes are possible, and we have proposed models in both regimes directly usable for circuit theory. The two regimes are extremely different, but both exhibit synchronization behaviors, which make them suitable for unconventional computation schemes, where the basic element (nanooscillator) provides considerably more functionality than traditional electron devices. This possibility interrogates a new way to design electronic circuits, and is especially relevant for bioinspired schemes, as biology itself relies on very rich nanodevices. Nevertheless, this idea comes with severe

challenges, the most important being the need to deal with variability inherent to all nanodevices. Therefore, this work opens the way to important research to make electronics based on nanooscillators a reality.

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