Spin torque nanodevices for bio-inspired computing

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***Abstract*—Spin torque nanodevices are smart magnetic components for which fast current-induced resistance variations can be obtained thanks to the fine interplay between electronic transport in magnetic multilayers and non-linear magnetization dynamics. By playing with the device dimensions, shape and bias conditions, but keeping the same magnetic stack, it is possible to design and implement a rich variety of functions, such as binary memory, random number generators, microwave oscillators, microwave detectors, spin wave emitters, memristors and more. This versatility combined with almost unlimited endurance, sub-ns dynamics and CMOS compatibility make spin torque nanodevices the ideal building blocks for bio-inspired computing.**

I. Introduction

SPIN torque nanodevices are based on magneto-resistance (giant or tunnel) effects [1,2] for reading the magnetization configuration, and spin transfer torque [3,4] for inducing fast magnetization dynamics. The spin transfer torque relies on a transfer of angular momentum from the conducting spins towards the localized moments, and creates noticeable effects for current densities of the order of 10^7 A.cm^{-2}. This phenomenon therefore appears only at the nanoscale, and its efficiency increases when the elements size is scaled down. Thanks to the high endurance and CMOS compatibility of spin torque driven magnetic tunnel junctions, spin transfer torque will be the writing mechanism of the new generation of magnetic random access memories (ST-MRAMs) currently under industrial development [5]. The force exerted by spin transfer on the magnetization can be categorized in two torques with controllable relative amplitudes: the first one acting like a current-induced magnetic field and the second like a damping or an anti-damping depending on the current sign [3]. Thanks to this double action, by carefully choosing the magnetic stack, sample shape, and bias conditions (current and field), the spin transfer torque can be designed to generate a wide variety of magnetization dynamics. The latter translate in a rich palette of resistive variations by application of a bias across the junction. Thanks to the recent progress in understanding the microscopic mechanisms underlying spin transfer torque it is now possible to predict and even design the response of spin transfer torque devices through coupled spin transport and micromagnetic numerical simulations. Demonstrated examples of functional devices are two-state non-volatile memories [6], random number generators [7], microwave tunable oscillators [8], microwave detectors [9], spin wave emitters [10], and more recently, memristors [11]. This wide range of functionalities combined with their CMOS compatibility makes spin torque devices ideal building blocks of hardware bio-inspired architectures [12].

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II. Motivation for spintronic bio-inspired architectures

If many different concepts of computing concepts inspired from biology have been proposed, most of them share the three following common points: they are massively parallel, composed of analog components with a relatively uniform architecture. For these reasons, bio-inspired architectures are fast, defect tolerant and can operate with a very low energy demand. In the current context where the efficiency of our classical processors is mainly limited by heating problems, these qualities are extremely valuable. The most well-known class of bio-inspired systems is artificial neural networks, inspired from the brain. These algorithms are very competitive for tasks such as recognition, classification, mining, that of great relevance today for managing the data deluge. However, implemented on sequential processors, artificial neural networks and bio-inspired architecture in general lose some of their most interesting performances (again the speed, defect tolerance, limited energy consumption) at the same time as they are deprived of their parallel architecture. There is therefore a strong incentive to build bio-inspired hardware that could complement classical processors in order to perform dedicated tasks such as classification at a low energy cost. But the great challenge relies in the wiring. The performance of bio-inspired systems increases with their size and degree of interconnection. For example, in the brain, there are about 10^{11} neurons and 10^{15} synapses. Realizing artificial neurons and synapses using CMOS is of course possible but takes a nonnegligible surface on silicon because it requires typically tens of transistors and passive devices. To reach the very high density of computing units and plastic non-volatile connections typical of biological systems it would be very interesting to mimic the properties of synapses and neurons at the nanoscale. Spin torque nanodevices, with their multiple, tunable functionalities and CMOS compatibility are therefore particularly adapted for this purpose. This assessment has been reached by a number of groups recently, leading to several proposals of bio-inspired architectures including one or several type of spin torque nanodevices [12].

III. PROMISING SPIN TORQUE BIO-INSPIRED SYSTEMS

For now, most spin torque bio-inspired computing concepts are neuromorphic systems, in other words inspired from the brain. There have been in particular several recent proposals of spin torque neurons and synapses relying on different implementations [13,14]. Another interesting system is associative memories based on synchronized spin torque microwave oscillators [15]. In that case the spin torque nano-oscillators emulate neurons and the synapses are replaced by a tunable coupling strength between oscillators. In this context, we have investigated the possibility to use noise to enhance the computing abilities of coupled spin torque systems. In particular, we will present numerical simulations and experiments demonstrating that reducing the energy barrier for the magnetization below k_BT allows phase-locking spin torque nanodevices at very low energy cost.

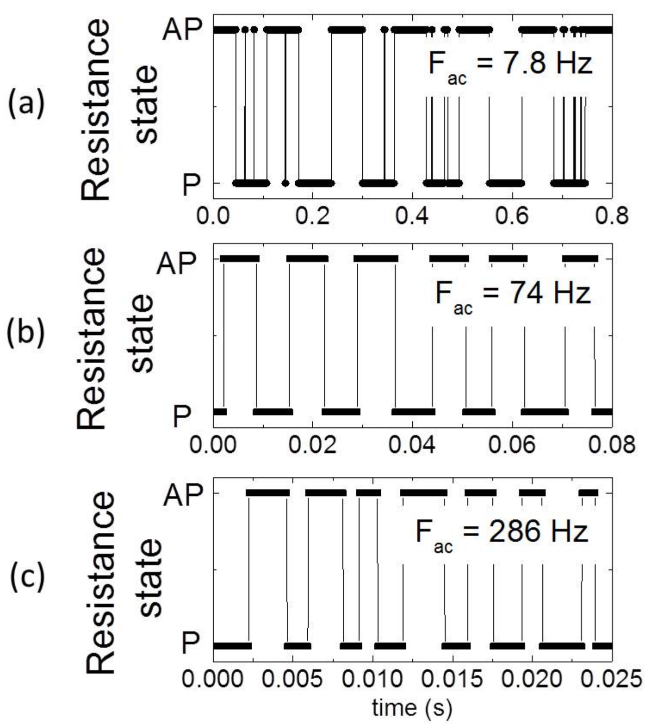

Fig. 1. Resistance as a function of time of a superparamagnetic tunnel junction driven by a periodic square wave current of fixed amplitude 200 µA and varying frequency. When the frequency of the injected current matches the frequency of the stochastic nano-oscillator, noise-enhanced synchronization occurs (panel b).

For example Fig.1 shows the stochastic resonance of a superparamagnetic tunnel junction to an input square wave periodic current of fixed amplitude (200 µA) and varying frequency. As can be seen from the middle panel (b), when the injected current frequency matches the natural mean frequency of the stochastic oscillator noise enhanced synchronization occur. These results pave the road for the spintronic implementation of compact and low energy demand associative memories and neuromorphic architectures based on coupled oscillators..

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