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Bottom-up approach for the fabrication of spin torque nano-oscillators

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Abstract

We report on a bottom-up approach for the fabrication of spin-transfer nano-oscillators (STNOs). Porous alumina is used as a template for the growth by electrodeposition of metallic spin valves in series. Under specific magnetic field and injected current conditions, emission of microwave current is detected with frequency in the 1.5 GHz range and linewidth as low as 8 MHz. We find strong indications that the microwave emission is due to spin-transfer-driven vortex oscillations. This technique is promising for the fabrication of dense arrays of STNOs in view of device synchronization.

(Some figures in this article are in colour only in the electronic version)

Spin-transfer torque-driven precession of magnetization is known to lead to emission of a microwave current [1]. The spin-transfer nano-oscillator (STNO) is often presented as a new class of nanoscale-sized microwave generator. Significant progress has been achieved recently in reducing the linewidth [2] and increasing the power of a single device, using STNOs having a vortex in one of the magnetic layers [3, 4]. However, these characteristics (linewidth and power) are still far from targeted applications. A commonly believed solution to overcome this issue is to synchronize several STNOs. Coherent emission of a small number has been observed in a few studies [5, 6]; however, the extension of such synchronization to large arrays of STNOs implies important technical challenges. One of those [7] arises from the fact that in a parallel connection of different STNOs, which is the most widely used connection scheme [5, 6], STNOs shunt each other. As a result, the total emitted power of even perfectly locked STNOs can go down with the number of oscillators. Therefore a series connection of STNOs is very desirable, which is a big technological challenge using the standard top-down lithography processes.

Here we demonstrate that these issues might be tackled using a bottom-up approach for the fabrication of STNOs by electrodeposition. It consists in electrodepositing metallic spin valves in series into nanoporous templates such as alumina [8] or polymer membranes [9]. To give some order of magnitude, up to 2×10^{11} spin valves per cm^2 may be electrodeposited into a 1 μm thick alumina template with 8×10^9 pores per cm^2. Moreover, the diameter inside a single pore is constant along its whole length, which is much more difficult to achieve using classical top-down technologies. As a result, our technique has a real potential to fabricate in an extremely cheap and easy way, a dense array of long nanowires, each of them containing tens of STNOs.

In previous works, we demonstrated the feasibility of this approach, by achieving current-induced magnetization switching by spin-transfer effect in such a system [8]. In this paper, we show that microwave current emission is possible in electrodeposited nanowires leading to narrow linewidth spectra under specific applied magnetic field and current conditions. Micromagnetic simulations and analysis of the

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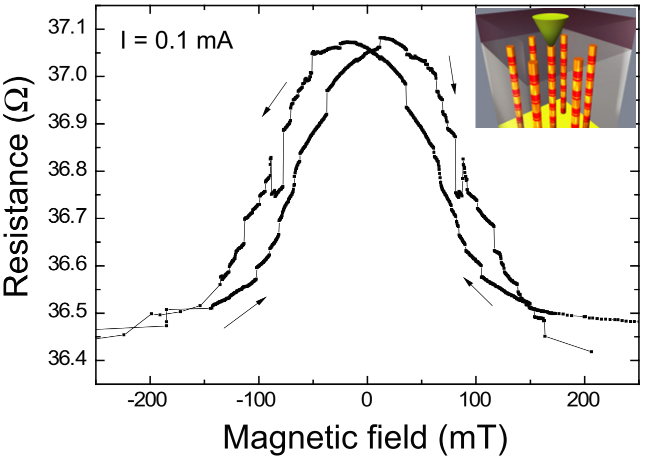

Figure 1. (*a*) Magnetoresistance of the six spin valves for a 100 μA current and magnetic field applied in plane. Arrows indicate the magnetic field sweep direction; (inset) schematic sketch of the device showing a nano-contact on top of a single nanowire into a porous alumina matrix.

spectral features of the emission lead to the conclusion that it can be associated with the spin-torque-driven oscillation of vortices in the magnetic layers.

Our system is based on nanowires grown by electrodeposition into 80 nm pores of 1.5 μm thick, lab-made porous alumina supported on a Si wafer. The single bath technique is used with composition as follows: Co(1M), Cu(15mM), H_3BO_3(0.5M). We have grown a stack of six spin valves [Co(7 nm)/Cu(10 nm)/Co(24 nm)/Cu(100 nm)]×6 further filled with Cu until the surface of the template is reached, following a technique described in a previous work [8]. The resulting sample is an array of parallel nanowires, each containing a stack of six STNOs as shown in the inset of figure 1. Details on the manner of electrically contacting a single wire within the dense array are given elsewhere [8]. Electric transport measurements are used to characterize the resistance and magnetic configuration of the samples, and microwave emission measurements are performed with a spectrum analyser after 25 dB amplification.

As we use a single bath electrodeposition technique, where both Co and Cu ions are present in the solution, a small amount of Cu is incorporated into the Co layers and their magnetization M_S is reduced as compared with bulk Co. Using ferromagnetic resonance, we characterized these layers and found out that M_S is reduced to 1200 emu cm^{-3} (versus 1370 emu cm^{-3} for electrodeposited pure Co); moreover, no magnetocrystalline anisotropy is present [10].

In figure 1, we show the resistance versus in-plane field (i.e. perpendicular to the wire's axis) of a single nanowire recorded at a current of 0.1 mA which exhibits a resistance variation of 650 mΩ. Several resistance jumps corresponding to reversal of the different magnetic layers are observed. Between two abrupt jumps, the resistance is seen to vary linearly in a way typical for nucleation, propagation and annihilation of vortices [11]. The rather broad distribution of switching fields and high saturating field may be ascribed to a non-negligible misalignment of the electrodeposited layers [12], as well as to the roughness of the Co/Cu interface [10].

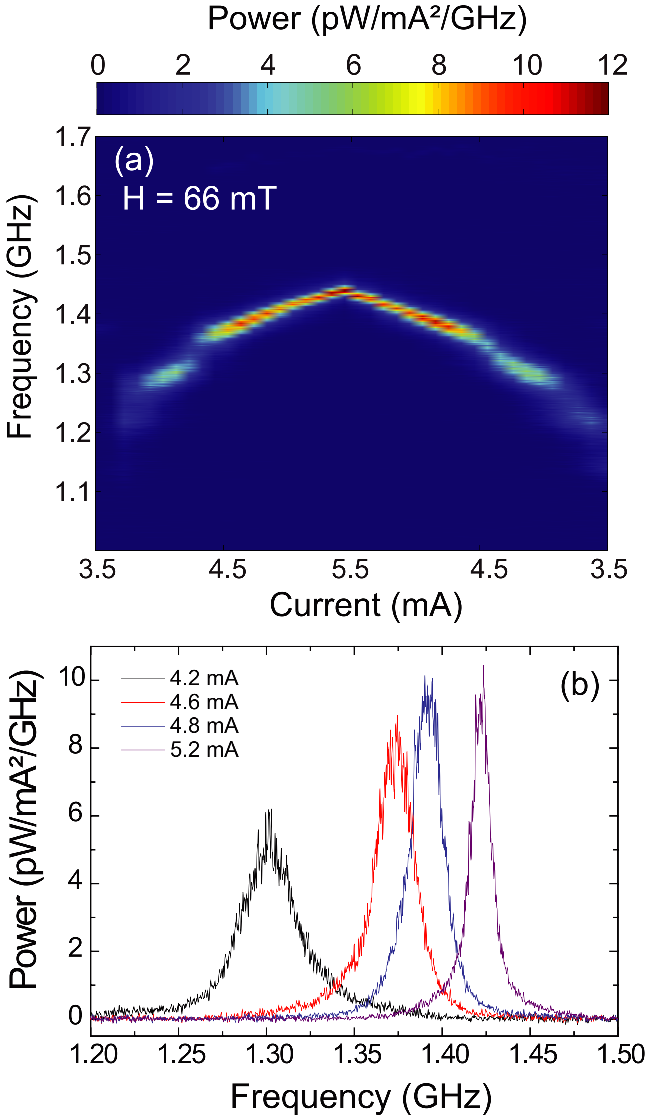

Figure 2. (*a*) Power map of the emitted microwave current as a function of the injected current back and forth for $H = 66$ mT, applied perpendicular to the layers. Two modes may be observed, with a transition around 4.4 mA. (*b*) Sample microwave spectra recorded under the same field conditions, for several injected currents.

On applying a perpendicular magnetic field and passing dc through a wire, we observe narrow peaks in the recorded spectra. We discuss below emission recorded for $H = 66$ mT; results for other fields are essentially similar. The power map for the microwave signal at this particular field is represented in figure 2(*a*) and selected spectra are shown in figure 2(*b*). It is obtained after saturation at zero current in the perpendicular direction; then the current is swept back and forth from zero up to 5.5 mA to avoid overheating of the sample. Microwave signal is detected at a threshold current 3.8 mA (7.6×10^{11} A m^{-2}), and its current tunability is low. A slight hysteretic behaviour might be noticed when the current is decreased, since the emission persists, albeit weak, below this threshold down to 3.5 mA. We note that such a hysteretic behaviour is a common feature of spin-transfer-induced vortex oscillation in a nanocontact [3, 13].

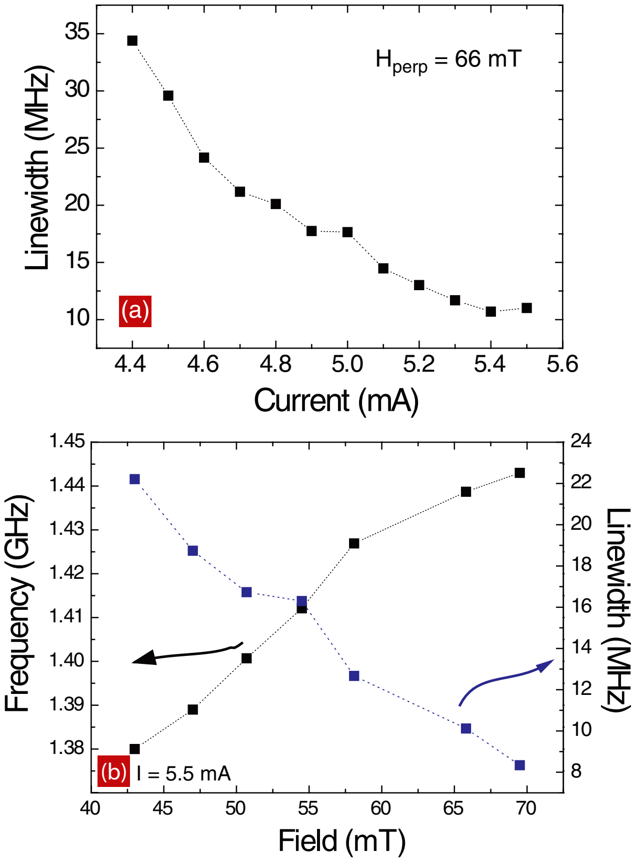

Figure 3. (*a*) Linewidth as a function of the injected current, for $H = 66$ mT. (*b*) Frequency (black squares) and linewidth (blue squares) as a function of the perpendicular field at 5.5 mA.

As we show in figure 3(*a*), the linewidth (Δf) decreases steadily with increasing current and therefore increasing spin torque that stabilizes the trajectory coherency. For the sample under consideration here, it may be as low as 8 MHz.

We observe similar behaviour for other applied fields. Looking at the influence of the magnetic field on the properties of the emission in figure 3(*b*), it appears that at 5.4 mA, a microwave signal may be observed after saturation between 70 and 40 mT. For this particular sample, no emission could be detected outside this range.

To gain a better insight into the micromagnetic nature of the microwave emission, we perform micromagnetic simulations to identify the remanent magnetic state of our system. We simulate the relaxation of the magnetization in Co disks 80 nm in diameter and different thicknesses, varying from 5 to 40 nm. Simulations are performed using the micromagnetic solver SpinPM. We use the following parameters for Co: $A = 1.3 \times 10^{-6}$ erg cm^{-1}, $\alpha = 0.01$, $M_S = 1200$ emu cm^{-3} and no magnetocrystalline anisotropy. The step of the computational mesh is 2×2 nm^2 in the plane and 3.5–6 nm in the perpendicular-to-the-plane direction. It is found that for the disks with thicknesses larger than 20 nm vortex state is the only possible stable magnetic configuration. This means that even if such a disk has been previously saturated, it jumps back to the vortex state on releasing the field. This feature becomes even more prominent if a perpendicular-to-the-plane field is applied: in this case, magnetic disks can be only in a vortex configuration for even smaller thicknesses (e.g. for 15 nm at $H_{\text{perp}} = 30$ mT). Moreover, the vortex is found to be a metastable magnetic configuration for disks of smaller thicknesses (down to 5 nm); if such a disk is initially in a vortex state, it is stable and the vortex is not expelled. At last, the Oersted field generated by the current flowing through the nanowire also significantly contributes to the vortex stability. From these numerical results we conclude that there should be a vortex at least in the thick magnetic layers of the emitting spin valve.

We also note that a comparison of our experimental data with that of previous experimental works [2–4, 13] on vortex-based STNOs, similarly to our numerical results, leads us to conclude that in our system, the emission is due to spin-transfer-driven vortex excitation. Indeed, the relatively low frequency of the emission, low linewidth (8 MHz) and tunability ($\partial f/\partial I \simeq 50$ MHz/mA) are prominent features of the spin-transfer-excited vortex modes. The field dependence of the frequency shown in figure 3(*b*) is also consistent with this conclusion. The oscillation frequency increases with increasing field in a way similar to that reported by De Loubens *et al* [14], suggesting that the core polarity is aligned with the field. We conclude from these indications that the measured microwave emission is associated with spin-transfer torque-driven vortex oscillations. In addition, as shown in figure 3(*b*) the linewidth decreases with increasing perpendicular field intensity. This is consistent with an out-of-plane tilt of the polarizer layer leading to a larger spin torque efficiency and therefore to a more coherent vortex core trajectory [4, 15–17].

To summarize, we have fabricated dense arrays of stacked metallic spin valves electrically connected in series. In such devices, microwave current emission was measured under proper current and magnetic field conditions. The spectral features of this emission, supported by numerical results indicate that it can be associated with the spin-transfer-driven motion of magnetization vortices. Given the recent progress in the fabrication of perfectly ordered pores' arrangement in porous alumina [18], this system is promising for microwave device applications since it allows connection of a huge number of metallic spin valves in series and/or parallel, which could lead to high-quality coherent emission by synchronization.

Acknowledgments

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