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Multiple-mode excitation in spin-transfer nanocontacts with dynamic polarizer

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We report our study on the emission response of a magnetic nanocontact with dynamic polarizer in perpendicular magnetic field. In this configuration three modes are accessible, two of which correspond to the precessional motion of a vortex in one of the two ferromagnetic layers with the other working as a static polarizer. At high currents a third mode can be observed that is ascribed to the simultaneous precession of two vortices, one in each layer, with the other layer working as a dynamic polarizer. © *2011 American Institute of Physics*. [doi:10.1063/1.3600328]

A dc spin-polarized current can excite multiple high-frequency modes in a nanodevice through spin-transfer torque (STT).[1,2] The highest frequency mode is represented by the excitation of the quasiuniform magnetic configuration in a nanomagnet and can reach frequencies as high as 50 GHz.[3] The nanomagnet is kept in a quasiuniform configuration by the application of a large magnetic field. The lowest frequency mode is the excitation of the precessional motion of a magnetic vortex around its equilibrium position.[4,5] This mode has frequencies of the order of hundreds of megahertz but no magnetic field is required,[6–8] which makes it very interesting for applications. Recently, a new class of dynamic states, which can be called windmill-like states,[1,9] has raised interest.[6,10] When in a spin-transfer device neither of the ferromagnetic layers has an easy in-plane anisotropy axis, high-frequency dynamics can be simultaneously excited in both layers with each of them working as a dynamic polarizer for the other. Two modes were observed, which could be accessed by changing the bias current. An insight into the physics behind the excitation of multiple modes in nanocontacts with dynamic polarizer has recently been gained by Kuepferling *et al.*[10] by conducting a systematic study of the dynamics of the system in magnetic field applied in the film plane.

We here report our study on the emission response of a nanocontact device with dynamic polarizer in perpendicular magnetic field. In this configuration, the external field is not in competition with the Oersted field self-generated by the bias current and does not induce any in-plane anisotropy. This allows us to gain access to a third mode. The interpretation of our experimental results supports the hypothesis that the main coupling mechanism between the two ferromagnetic layers is mutual SST.

The spin valve structure was deposited by sputtering and comprised the following layers: Cu(40 nm)/Py(4 nm)/Cu(6 nm)/Co(15 nm)/Al(4 nm). The multilayer was patterned into a typical squared U-shaped microwave ground electrode, the middle side of which was 40 μm wide and 200 μm long. The nanohole was opened at the center of the middle side by atomic force microscope nanoindentation and plasma etching into a 180 nm thick resist. A top electrode of Al(100 nm) was subsequently deposited and patterned by standard photolithography to form a coplanar waveguide. In the following, positive current means electrons flowing from the Co layer to the Py layer.

In Fig. 1 we show the power spectral density in an $H_\perp = 24$ mT perpendicular applied field. Three modes are accessible. Although in the experiment the maximum current was first applied and the map was taken by stepping down the current, let us consider first the low frequency/low current mode. The interpretation of this mode is straightforward. While large currents can stabilize a vortex in each of the ferromagnetic layers, at low currents the vortex in the thin Py is not stable and the magnetic configuration in this layer is in a single domain state under the contact. The vortex in the Co precesses around the contact at frequencies that are consistent with those reported in nanocontacts with uniformly magnetized polarizer.[5,11] As a matter of fact, this mode is the one with the largest power (see Fig. 2).

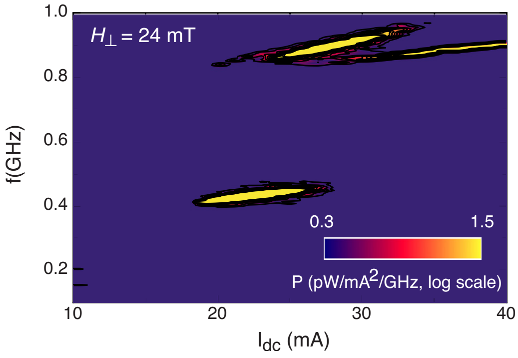

FIG. 1. (Color online) Map of power spectrum amplitude vs frequency and applied current bias I_{dc}. A field of 24 mT was applied perpendicular to the sample plane.

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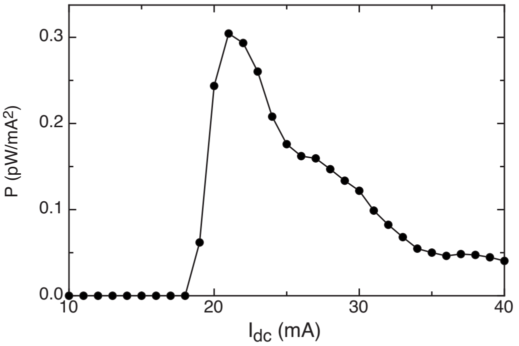

FIG. 2. Power integrated on the entire spectrum at fixed applied current bias I_{dc}.

Let us now consider the mode observed at the highest currents. In agreement with Kuepferling *et al.*,[10] we assume that the large current stabilizes two vortices, one in each of the two ferromagnetic layers. We will verify this assumption *a posteriori*. Since the local STT is inversely proportional to $M_S d$ (Refs. 1 and 9) (with M_S and d the saturation magnetization and layer thickness, respectively), the vortex in the Py is subject to a stronger STT as compared to the vortex in the Co. The vortex in the Py precesses and since the frequency of precession is inversely proportional to the film thickness,[5,12] it is not surprising that this mode has fairly higher frequency as compared to that due to the precessional motion of the vortex in the thick Co at low currents. Yet, the vortex in the Co cannot be static because, in the absence of in-plane field, its resting position would be the contact center and, therefore, no signal would be generated on the device electrodes. Local STT in the Co must be not negligible and the vortex in this layer precesses at lower frequency. In this range of currents the system is in a windmill-like precession, with the angle between the magnetization vectors not being constant.

We can exclude that the Co is in a single domain state under the contact. First, the observation of a vortex precession in the Co at low currents suggests that, most likely, the vortex was nucleated at higher currents. Besides, if one assumed that the Co is in a single domain state under the contact, a gyrating vortex in the Py should, either generate the same power as in the case, previously discussed, of precession of Co vortex with static and uniform Py polarizer, if the vortex gyrates far away from the contact, or the output power should dependent on the bias current, if the vortex gyrates under the contact area.[12] Instead, the output power is about six times smaller (see Fig. 2) and does not change with the current in the range where only this mode is detected. We can unambiguously conclude that the Co is in a vortex state under the contact and, since no field is applied in the plane, the vortex in this layer precesses under the action of the STT exerted by Py. With the same argumentations one can conclude that the opposite is true. The Py is in the vortex state and is precessing under the action of the STT exerted by the Co. The Co is behaving as a dynamic polarizer for the Py and vice versa.

In the windmill-like state the two vortices are within the electrically active area of the device because of the strong restoring force generated by the large current. With the current decreasing, the vortex in the thin Py would be the first one to be expelled if the approximation of infinite straight conductor could be considered reasonably valid for the current distribution. Yet, the appearance of a third mode at intermediate currents that has larger power, larger frequency and larger tunability as compared to the windmill-like mode suggests that not only is the vortex in the Co expelled first but the Co layer behaves as a static polarizer for the vortex in the Py. In order to understand the reasons of this behavior we computed the current distribution across the nanocontact. The simulations[13] showed that the current distributions in the two ferromagnetic layers are substantially different. Even assuming ideal interfaces, the current spreads in the spacer because of the smaller resistivity of the Cu as compared to that of Co and Py. As a result, the electrically active area in the Py is at least two times larger than that in the Co. Since the Py is sandwiched between two Cu layers, the in-plane component of the current distribution is negligible in this layer. Instead, in agreement with the computations performed on a similar system,[14] the in-plane component of the current distribution in the Co is not negligible at the edge of the nanocontact. When the vortex in the Co approaches the border of the electrically active area, this in-plane component exerts an additional torque that favors expulsion of the vortex.[12] Finally, the simulations show that the Joule heat density in the Py is about three times smaller than that in the Co, under the contact. This is because the Py is sandwiched between two Cu layers that work as heat sinks. At high currents, when the two vortices are both under the contact, the vortex in the Co sees a substantially larger increase in temperature as compared to that in the Py.

All these numerical results support the following scenario. The vortex in the Co is ejected from the contact area and leaves a quasiuniform magnetic configuration under the contact, which results in an increase in the power. The power never reaches the same value as the low current mode but in Fig. 2 a plateau is reached where the power is about half of the maximum. This confirms that the vortex in the Py is still within the electrically active area. Since the Co is no longer following the Py, the frequency and the tunability of this mode are higher as compared to the windmill-like mode.

This mode is metastable and coexist with the windmill-like mode. This means that the vortex in the Co is periodically renucleated. It has been experimentally found that, in nanocontacts with similar diameters and current amplitudes, vortex nucleation occurs in a few nanoseconds.[15] Since the vortex in the Py is gyrating at a frequency ~1 GHz (see Fig. 1), which means the period of oscillation is ~1 ns, the vortex in the Py has the time to make several turns, before the windmill-like state is temporarily re-established. Since the spectrum is acquired on a timescale much longer than the cycling time, the two modes appear simultaneously in the power spectrum but they are not coexistent in time.[6,8]

When the current is further reduced below a critical value (about 27 mA in Fig. 1) for stabilization/destabilization of the vortex in the Py, this vortex annihilates leaving a uniform configuration under the contact area. The STT on the Co increases and this stabilizes the low-current mode in which the Py behaves as a static polarizer and the vortex in the Co gyrates outside the electrically active area. In a small range of currents around this critical value, the three modes appear simultaneously in the spectrum. This is not surprising because nucleation of the vortex in the Py, as well as in the Co, is a stochastic process and thermal effects play an important role.[15] In any case, the value of the integrated power in Fig. 2, in the range of currents where multiple modes are

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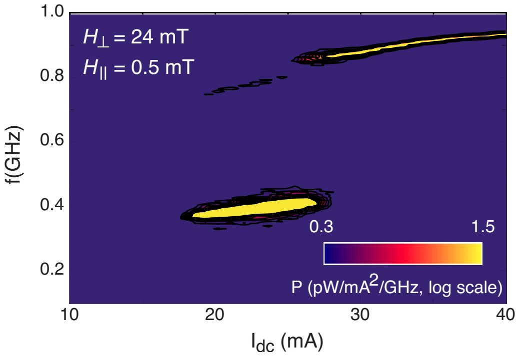

FIG. 3. (Color online) Map of power spectrum amplitude vs frequency and applied current bias I_{dc}. A field of $(H_\perp, H_\parallel) = (24, 0.5)$ mT was applied.

simultaneously detected, should be taken into account bearing in mind that in frequency-domain measurements it is not possible to estimate the fraction of time the system spends on each mode and, hence, the contribution to the total integrated power.

The characteristics and the existence itself of the mode at highest frequencies strongly dependent on the specific geometry of the device, i.e., thickness and relative position of the two ferromagnetic layers in the stack, and on the specific measurement configuration. For the device geometry used here, this mode is metastable and never exists alone (see Fig. 1). The application of an in-plane field (see Fig. 3) as small as 0.5 mT completely suppresses it. An in-plane field elongates the orbit of the vortices and off-center them.[8] The displacement is inversely proportional to the product $M_S d$,[10,16] therefore the vortex in the Py is particularly sensitive to the field. At intermediate currents and in absence of in-plane field, when the vortex in the Co is expelled from the contact, the STT on the Py suddenly increases. As a consequence, the orbital radius of the vortex in the Py increases and can approach the edge of the electrically active area. When the in-plane field is applied, the elongation and the displacement of the orbit favor expulsion and subsequent annihilation of the vortex in the Py. Therefore, the metastable mode is suppressed.

It is interesting to note that a nonlinearity between the frequency and the current in the windmill-like mode can be now appreciated (see Fig. 3). The tunability decreases with the current. This was not evident in Fig. 1, where this mode exists alone in a smaller range of currents. This behavior is in agreement with the theoretical prediction[12] of a nonlinear dependence of the radial distance of the vortex with the current in the small amplitude limit and enforces the assumption that the vortices are just below the contact.

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