# Electric Switching of Magnetic Vortex Cores in Nanodisks

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**The planar vortex structure is a fundamental microscopic arrangement of the magnetization in sub-micron sized soft-magnetic ferromagnets. Its particular dynamic and static properties have triggered a large amount of interest in the last years. In particular, the vortex core – a thermally very stable, tiny region of only about 10 nm size in which the magnetization points perpendicular to the plane – exhibits a perfect bistable behavior, which makes them interesting candidates for binary data storage. Recently, a simple method to switch these vortex cores by means of in-plane magnetic fields has been demonstrated. Using micromagnetic simulations, we have investigated the influence of electrical current pulses on the magnetic vortex structure of a 200 nm Permalloy disk. Our simulations predict that a controlled switching of the vortex core can be obtained by applying suitably shaped electric current pulses, inducing a rapid switching of the vortex core. Compared with the previously known field-induced switching, the electrical route introduces the technologically appealing possibility to integrate vortices in electronic circuits and to address single nanomagnets within dense arrays.**

In order to store information using a vortex core, mechanisms for a controlled switching of its orientation are required. Recently, it has been experimentally demonstrated that the vortex core could be switched by means of sinusoidal low field pulses applied in the plane of the sample [1]. In this case, the gyrotropic resonance was exploited: a low-frequency mode where the vortex rotates around its equilibrium position at sub-gigahertz frequency. In practice, the switching time can be defined as the time between the application of the field and the completion of the core switch. In this sense, the switching time of this resonant scheme is of the order of nanoseconds. Based on micromagnetic simulations, we have proposed a faster route to achieve the core reversal [2]. In this case, which does not use the gyrotropic resonance, the reversal is induced by a suitably shaped unipolar in-plane magnetic field pulse only a few picoseconds long. The switching of a vortex core by means of a magnetic field however presents a problem in terms of applicability: The lack of selectivity of individual elements. Reliably addressing a single nanodisk inside a dense array is very difficult using external fields. By means of advanced simulation techniques we found a new, fast and simple method to switch magnetic vortex cores by applying short *electric* current pulses, only one hundred picoseconds long [3]. The electric current pulse is applied in the plane of the element. We thus show that a fast toggle core switching mechanism can be triggered in a relatively simple way which is compatible with integrated circuits, thereby solving the issue of selectivity.

The study was performed using micromagnetic finite-element simulations based on the Landau-Lifshitz-Gilbert equation. We extended our micromagnetic code used in previous simulations [2] to consider the effect of the spin torque exerted by an electric current flowing through the sample. As a model system, we consider a disk-shaped Permalloy (Py) sample of $d = 200$ nm diameter and $t = 20$ nm thickness. The sample was discretized into ca. 216,000 irregular tetrahedral elements, corresponding to a cell size of about 3 nm. A homogeneous current density distribution was assumed.

The current-induced vortex core reversal was studied for short Gaussian-shaped current pulses ($\sigma = 100$ ps) of varying strengths. To obtain a core reversal, we found that for the considered sample the amplitude of these pulses must exceed a minimum value of $j$=6.7$\cdot 10^{12}$A/m$^2$. Although such a high current density might endanger the structural stability of the sample if it was applied continuously, the damaging effects of the current should be small in the present case where only ultrashort pulses are used.

A typical example of the vortex core reversal process is shown in Fig. 1, starting with a vortex whose core is pointing in the positive $z$-direction. Interestingly, the micromagnetic processes leading to the vortex core reversal with current pulses are identical to the ones we had previously found for magnetic field pulses [2]. To describe these processes in detail, we used an isosurface representation which precisely highlights the position of the vortex core. The core is located at the intersection of the $m_x = 0$ and $m_y = 0$ isosurfaces, *i.e* where the transverse component of the magnetization is maximal ($m_z = \pm 1$). As a result of the current flowing through the sample, the vortex structure is first heavily distorted and a pronounced out-of-plane “dip” in the magnetization is formed near

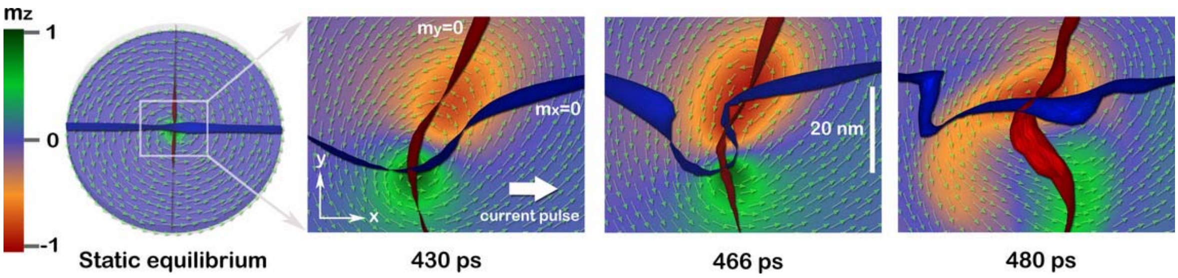


*FIG. 1:* Current-induced vortex core reversal in a Py nanodisk of 200 nm in diameter and 20 nm thickness. A Gaussian current pulse is applied in the sample plane with a strength of 7.4$\cdot 10^{12}$ A/m$^2$ and a width $\sigma = 100$ ps. The magnetic vortex structure at equilibrium is shown on the left. In the three frames on the right, the evolution of the magnetization is shown for a small region around the vortex core, where a vortex-antivortex pair nucleates. As the vortex is shifted in the direction of the electron flow prior to the pair creation, these frames are not taken in the same areas of the sample. The arrows represent the in-plane magnetization direction, while the color code displays the *z* component of the magnetization. The blue and red ribbons are the $m_x = 0$ and $m_y = 0$ isosurfaces, respectively. The time is measured from the moment the pulse is applied.

the vortex core. About 460 ps after the application of the pulse, the increasing distortion leads to the creation of a vortex-antivortex pair, which can unambiguously be recognized by the two additional crossings of the $m_x = 0$ and $m_y = 0$ isosurfaces. Both cores of the new pair are pointing in the opposite $z$-direction of the initial core [2]. The newly formed antivortex and the oppositely polarized initial vortex subsequently annihilate [4]. The latter subprocess unfolds over approximately 10 ps and leaves a single vortex core, which is oppositely polarized with respect to the initial one. The formation of vortex-antivortex pairs after application of short current pulses is consistent with recent experimental observations by Kläui *et al.* [5].

By increasing the pulse strength, it is possible to produce multiple switches. Multiple switches are a repeated series of vortex-antivortex pair creation and annihilation processes. The diagram in Fig. 2 shows the number of core switches as a function of the applied current's strength. Clear thresholds are observed. While the core reversal mechanism is mediated by the formation of a vortex-antivortex pair, it is the annihilation process which leaves the vortex with an oppositely-polarized core. As we demonstrated in Ref. [4], such an annihilation process is connected with a magnetic singularity (Bloch point). Since the energy of formation of a Bloch point is uniquely a function of the exchange constant, the annihilation (and thus the core reversal) process can only occur at specific energy values, resulting in the observed steps. A double core switching is obtained with current pulses of about 8.5$\cdot 10^{12}$ A/m$^2$, while triple and quadruple switches occur with pulses of 10$\cdot 10^{12}$ A/m$^2$ and 11$\cdot 10^{12}$ A/m$^2$, respectively. Ultimately, for very large currents (above 20$\cdot 10^{12}$ A/m$^2$), the vortex core is expelled from the sample.

In conclusion, we have presented the possibility of reversing the polarization of a magnetic vortex core using short current pulses. The magnetization reversal process, which consists of a complicated sequence of vortex-antivortex pair creation and annihilation events, unfolds on a time scale of ca. 40 ps, *i.e.* shorter than the duration of the pulses applied

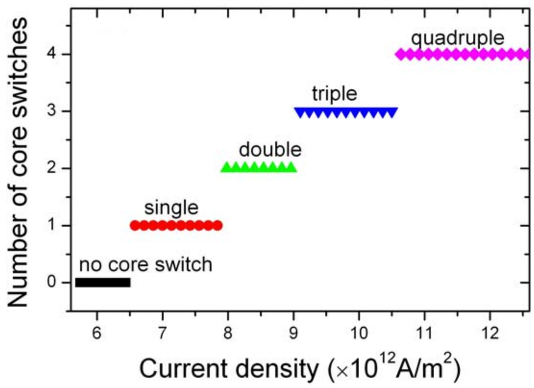


*FIG. 2:* Number of times the vortex core switches as a function of the applied current density.

in this study. Further investigations are required to explore the limits of the operational range for a controlled, single toggle switching in terms of pulse duration and pulse strength, and to determine how short a current pulse can be to trigger a vortex core reversal. The current-induced vortex core reversal opens the possibility of addressing individual magnetic elements in a vortex state within an array of nanoelements. This feature could make vortex cores interesting candidates for data storage purposes in future devices.

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