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Research articles

Decreasing the size limit for a stable magnetic vortex in modified permalloy nanodiscs

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ABSTRACT

This work proposes the use of tower-like structures (small diameter cylinders) embedded on nanodiscs in order to reduce the minimum size of disc diameter to sustain a vortex as ground state. By simulating the dynamics of nanostructured discs of Py-79, we demonstrate that the geometric modification of piling smaller diameter cylinders on top and bottom of a larger diameter disc, introduces a large out-of-plane anisotropy, which in turn allows for the tailoring of stable vortices, even as the diameter of disc and cylinders are greatly reduced, down to dozens of nanometers. This geometric modification is in contrast to the same result (of decreasing the overall size of structures containing vortices) if we introduce vacancies inside a nanodisc, turning it into a ring shaped structure. Such ring structures, while experimentally easy to achieve and also allowing for a stable vortex to form with a well defined chirality, act as an attractive site for vortices, effectively diminishing or completely eliminating the polarity component of the vortex. The proposed tower structures, however, are shown to not only preserve both vortex chirality and polarity, but also exacerbates the polarity, thus increasing the stability of the vortex ground state by pinning. This result introduces the possibility of creating devices that require a reliable magnetization profile, in the sense that the vortex becomes strongly pinned to the tower, which also has a well defined magnetization, rather than being bound to a vacancy which may potentially collapse the ground state. Upon constructing magnetization phase diagrams for regular discs and discs that contain these tower-like structures, we conclude that the latter are appropriate candidates for a high density, high reliability device, suitable for potential applications that require vortex pinning, such as in biomedicine and computation.

1. Introduction

Recent improvements in research on magnetic nanostructures have proven to be a fertile ground for the most diverse applications, and understanding the physics of these structures is an exciting topic for both theory and experiment. In biomedicine [1] these magnetic nanostructures may be remotely controlled to interact with living tissues performing drug delivery at specific locations. The use of Permalloy microdiscs has been shown as effective in destroying cancer cells through the interaction of a magnetic vortex with oscillating magnetic fields [2]. They can be produced for this purpose with a high yield, and thus very good contenders to becoming a medical treatment [3]. Magnetic nanostructures have also been intensely studied due to improved data storage and increasing information density. Cylindrical nanostructures, for example, are promising candidates for a nonvolatile MRAM unit [4]. Moreover, studies have shown the possibility of injecting spin polarized currents from a ferromagnet into a semiconductor [5,6] open a new window for the development of spintronic devices.

To achieve a higher level of applicability regarding these magnetic structures, increasingly more knowledge about the equilibrium and dynamic aspects of their composing elements is required. We do this mainly by specifying the sample's *magnetization*, which is the measure of how much a system reacts due to the presence of a magnetic field from an external source. In particular, disk and cylinder shaped nanostructures are an interesting target for studying, due to their potential in becoming high density recording devices and efficient sensors at the nanoscale [7].

There are three very well known equilibrium states of magnetization for ferromagnetic cylindrical nanostructures [8]. Two of these states have fully saturated configurations in which the magnetization lies either along the cylinder's axial (out-of-plane) or radial (in-plane) directions. For these configurations the boundary

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of the nanostructure is relevant, because the demagnetizing field due to the dipole interaction among magnetic moments leads to deviations in the direction of magnetization at the boundary. From now on we will refer to the in-plane alignment of magnetization as C-plane state or simply C-state. Another equilibrium state consists in a magnetic vortex, with a curling radial in-plane magnetization and an out-of-plane component perpendicular to the cylinder radius. These vortices are known to appear as a result of the competition among short range exchange interactions due to localized magnetic moments and the long range demagnetizing field created across the whole cylinder [9,10]. A vector plot of the C-state and vortex magnetization fields for a nanostructured disc is found in Fig. 1.

Manipulation of the magnetization states for applications is done mostly through external magnetic fields in order to introduce perturbations to the ground state, leading to phenomena such as gyrotropic excitation modes and switching [11]. It is most relevant in general to modify a material in order to change both the ground state and its response to the external applied field, leaving it suitable for many different purposes [12,13]. This can be done, for example, by doping with impurities, ferromagnetic or not. One of the most popular materials is the Nickel-Iron alloy Permalloy or simply Py. Much has been done in the matter of introducing magnetic impurities and using them to modify the structural properties of Py, experimentally and theoretically [14].

Another way to influence the ground state and its response to external fields in a ferromagnet is through its geometry. Several works have studied the way shape and different aspect ratios in nanostructures impact the equilibrium magnetization states [15–17], and these factors are important for vortex nucleation and annihilation mechanisms. In so called soft magnetic materials such as Py, global magnetostatic ordering trumps over the magnetocrystalline anisotropy due to unit cell ordering, and the emerging magnetic configurations in nanostructures become very sensitive to the geometric form and dimensions of the magnet [18]. The reason for structural modifications affecting the magnetization vector field then, is that the *shape anisotropy effects* driven by dipole interactions are modified. The number of nearest neighbors to any particular lattice point is also modified by changing the boundary, thus modifying the exchange interactions as well. The relationship of both factors contribute to a change in total energy which may accordingly increase or decrease surface effects, making the ground state size and shape dependant.

Different levels of stability and different ground states may be desired for any given application, and obtaining a detailed control of such states merely from structural modifications is an attractive choice compared to doping with (at times very expensive) materials, and also very doable experimentally, with techniques ranging on their degree of precision, such as epitaxial growth, dot array fabrication, and lithography, the latter with typical sizes up from 10 to 20 nm [19–21].

One interesting approach is to use a ring shaped structure to induce vortex formation in a nanomagnet, by introducing a diamagnetic defect (or vacancy) in a disk. This defect or vacancy can then capture and retain a vortex state, however, it significantly reduces or even vanishes the out-of-plane component [22–24], making it very hard to actually measure a logical state (a bit) due to the out-of-plane vortex field, in a potential memory device. Furthermore, potential applications in biomedicine and related areas for example, can benefit from a wider range of structures containing vortices as their ground state [25].

In this work we propose a simple structural modification to nanodiscs of $Ni_{79}Fe_{21}$ Py-79, in order to tailor shape effects and increase pinning of vortices, as well as decreasing the overall size of stable vortices. We start by describing the theoretical methods and computational tools developed for simulation and analysis, and then proceed to describe the considered structures and the

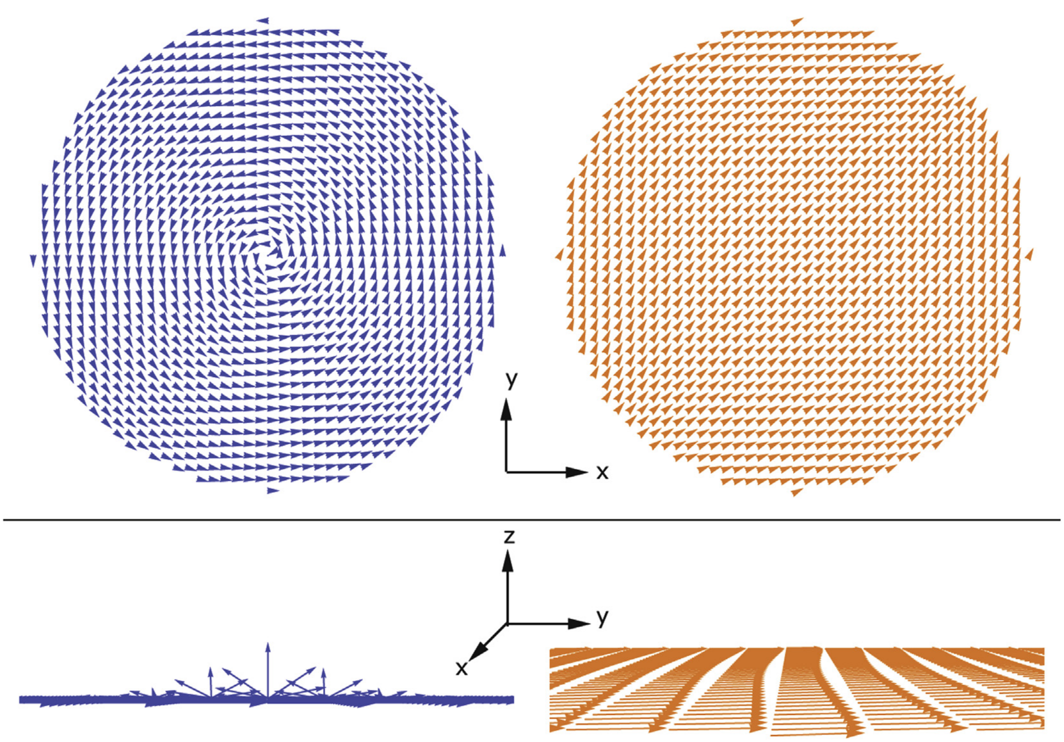

Fig. 1. Magnetization vector field for the vortex (up and bottom left) and C-state (up and bottom right) ground states. Note that for the vortex phase, the polarity (z-component) does not correspond to a full alignment along one direction, but rather a smooth curling profile around the vortex core. For the C-state, there is approximately no z-component at all and every vector lies along the XY plane. The vortex phase is shown on the YZ plane at the bottom for clarity. We denote by radial direction any vector lying on the XY plane, and axial direction by any vector lying along the z-axis.