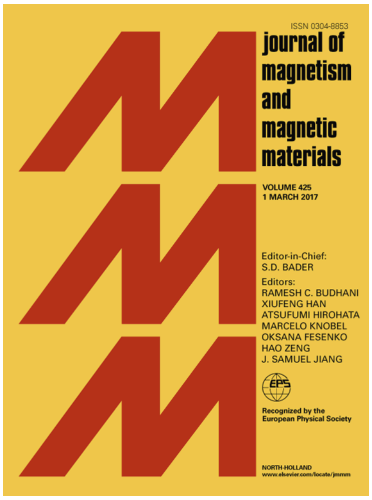

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Exploring Performance, Coherence, and Clocking of Magnetization in Multiferroic Four-State Nanomagnets

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Nanomagnetic memory and logic are currently seen as promising candidates to replace current digital computing architectures due to its superior energy-efficiency, non-volatility and propensity for highly dense and low-power applications. In this work, we investigate the use of shape engineering (concave and diamond shape) to introduce biaxial anisotropy in single domain nanomagnets, giving rise to multiple easy and hard axes. Such nanomagnets, with dimensions of ~ 100 nm × 100 nm, double the logic density of conventional two-state nanomagnetic devices by encoding more information (four binary bits: “00”,”11”,”10”,”01”) per nanomagnet and can be used in memory and logic devices as well as in higher order information processing applications. We study reliability, magnetization switching coherence, and show, for the first time, the use of voltage-induced strain for the clocking of magnetization in these four-state nanomagnets. Critical parameters such as size, thickness, concavity, and geometry of two types of four-state nanomagnets are also investigated. This analytical study provides important insights into achieving reliable and coherent single domain nanomagnets and low-energy magnetization clocking in four-state nanomagnets, paving the way for potential applications in advanced technologies.

Index Terms— **four-state nanomagnets, shape anisotropy, concave nanomagnet, magnetization dynamics.**

1. Introduction

The continued downscaling of conventional transistor-based electronics faces a challenging barrier in the form of increasing energy dissipation. In the quest for alternative paradigms, spin- and nanomagnet-based computing architectures [1]–[5] have emerged as promising candidates. Unlike transistor-based devices, nanomagnets experience a correlated switching of spins [6] and do not suffer from current leakage. As a result, these novel methodologies would not suffer from standby power dissipation and offer substantial benefits such as non-volatility, energy-efficiency, high integration density, CMOS-compatibility, and compact implementation of logic gates.

One of the most important properties of ferromagnetic materials is magnetic anisotropy. This intrinsic property of magnetic materials plays an essential role in magnetoelectric applications such as permanent magnets, information storage media and magnetic recording heads, which require the magnetization to be pinned in a defined direction. In nanomagnets, the magnetic anisotropy also depends on the shape of the nanomagnet and its magnetic properties can be engineered by manipulating the shape of the nanomagnet, with different shapes giving rise to different anisotropic behaviors.
Basic shapes of nanomagnets, such as ellipsoid and rectangular (having uniaxial anisotropy and encoding two states or two binary bits “0” & ”1”) have attracted a lot of attention for its applications in ultra-low power binary logic [7]–[11] and non-volatile memory applications [12]–[14]. Nanomagnets encoding four states, instead of the conventional two-states, have been theoretically demonstrated to implement Boolean logic [15], [16]. Besides increasing the logic density, this four-state scheme also holds promise for higher order computing applications such as associative memory, neuromorphic computing and image processing [17]. Since nanomagnetic logic devices require accurate propagation of magnetic information along dipole-couple nanomagnets, reliable switching behavior is paramount and has been shown to be dependent on shape geometry, with different shapes and playing an important role in the magnetization switching behavior and correlation lengths along an array of nanomagnets [18].

A four-state memory element can be implemented with a magnetostrictive layer (for instance, single-crystal Ni), which would exhibit biaxial magnetocrystalline anisotropy in the (001) plane [41]. Epitaxial films of single-crystal (001) Ni can be grown using molecular beam epitaxy (MBE) [19], [20]. Biaxial anisotropy in magnetic thin-films has also been shown in single-crystal films [21], coupled films [22], double-layer films [23], as well as in a four-pointed star-shaped structure [24], with the latter highlighting the relationship between shape-induced biaxial anisotropy and the geometry of a thin magnetic film element, indicating that in a four-pointed star-shaped structure, the high-energy states occur when the average magnetization, $\vec{M}$, was oriented from tip to tip (along the long dimension), while the low-energy corresponds to $\vec{M}$ pointing diagonally (45°, along the short dimension).

Another technique used to modify a nanomagnet’s magnetic anisotropy, similar to shape anisotropy, and termed ‘configurational anisotropy’, involves creating multiple “easy” axes by introducing small modifications to the uniform magnetization of nanomagnets of a specific symmetric shape [25]–[27]. In experiments conducted by Lambson et al. [28], the effect of configurational anisotropy on the magnetic properties of triangular-, square- and pentagonal-shaped nanomagnets was studied. It was observed that by modifying parameters such as sample thickness and concavity of an