Magnetization Configurations and Reversal of Magnetic Nanotubes with Uniaxial Anisotropy

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Nanotubes and nanotube arrays, combining the attractive tubular structure with magnetic properties, are promising candidates for potential applications in a broad range of nano-technological areas, such as high-density data storage, nano-electromechanical devices, as well as biotechnology, like drug delivery, biosensors, chemical and biochemical separations etc. [1]. Therefore, study of the magnetic properties of nanotubes, such as their magnetization (**M**) distributions, magnetization reversal processes etc. became one of the important research directions in modern nanomagnetism.

We present calculations of the magnetization configurations and reversal behavior of magnetic nanotubes with uniaxial anisotropy by means of 2D micromagnetic simulations and analytical methods. The equilibrium state, the hysteresis loops and the switching field values are calculated as functions of the tube sizes and material parameters. There is an additional degree of freedom for magnetic nanotubes in comparison to nanowires, their thickness, ΔR. The tube radii R from 50 nm to 150 nm and the tube length (L) /radius aspect ratio $5 \leq L/R \leq 20$ were explored. For a finite length of magnetic nanotubes the magnetization configuration is characterized by the uniformly magnetized along the tube axis middle part and two non-uniform curling states of a length L_c in two ends of the tube with the same or opposite magnetization rotating senses, referring as C-state, or B-state, respectively. We found that the magnetization configuration of the C-state exists for thin nanotubes with the tube thickness, ΔR, in the range of $\Delta R/R \leq 0.2$ [2]. For thicker nanotubes the strong magnetostatic stray field forces the change of rotating senses of the end domains in opposite directions (B-state) [3]. The transition from the C-state to a vortex state with in-plane magnetization is described as function of the tube geometrical parameters. The nanotube hysteresis loops and switching fields were calculated. A simple analytical model was developed to describe the nanotube magnetization reversal reducing its description to the Stoner-Wohlfarth model with effective parameters. The equilibrium state of nanotube is described by Θ, the angle of the magnetization **M** deviation from the intrinsic tube easy axis (Fig. 1). Θ as the function of tube aspect ratio L/R, tube thickness ΔR, and uniaxial anisotropy constant K_u obtained by minimizing the total energy of **M** containing the anisotropy, the magnetostatic, and the exchange energy terms, well describes the dependences of the shape of hysteresis loop and switching field values on tube geometric and material parameters in the C- and B-state. For thick nanotubes with reducing tube length the uniformly magnetized middle part gradually diminishes and disappears. The different types of domain walls, such as the transverse domain wall, the asymmetric vortex wall, branch fashion wall, as well as horse-saddle wall, are nucleated in the tube, leading to the wide variety of magnetization reversal modes. We present simulations of the domain wall types and magnetization reversal modes for short nanotubes with R of 50 nm and 100 nm.

In the magnetic field applied along the tube axis **z** the simulated hysteresis loops of C- and B-state tubes (Figs. 1, 2) consist of the reversible rotation to the stable states and irreversible reversal of the magnetization. The coercive field H_c and the switching field H_s, increase with increasing of K_u for the given size nanotubes, and decreases with increasing R for the nanotubes. With reducing nanotubes length and increasing tube thickness the domain walls with the varied patterns, such as the transverse wall, vortex wall, branch wall, and horse-saddle wall, determine **M** distributions near the centre of the tube. The domain wall structure and magnetization reversal modes demonstrate sensitive dependences on the tube thickness, ΔR. For short nanotubes of R=100 nm, with ΔR increasing to 40 nm, 50 nm, and 60 nm the domain walls are induced. The magnetization processes of such domain walls are characterized by the periodic transitions of the wall structures from the respective initial patterns to the final unique structure of the branch fashion wall, which causes no closure of the magnetization loops for the z-component of the magnetization at zero fields with respect to the initial and the final states.

The simulations were performed using the typical soft magnetic material parameters: the exchange constant, $A=10^{-6}$ erg/cm, and the saturation magnetization, $M_s= 10^3$ G. In order to study dependence of the magnetization configuration and magnetization reversal on the values of the uniaxial anisotropy constant, K_u, two values of $K_u = 5\times10^4$ erg/cm^3, and $K_u = 10^5$ erg/cm^3, were chosen that satisfy the soft magnetic materials condition of $M_s^2 >> K_u$. The exchange length of the material is $l_{ex} = \sqrt{A}/M_s = 10$ nm. The dependences of H_c, H_s on the tube geometry (L, R, ΔR) and material parameters (A, M_s, K_u) can be understood by the energy competition of the magnetostatic and Zeeman energy terms against the sum of the exchange and anisotropy energy terms.

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References

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Figures

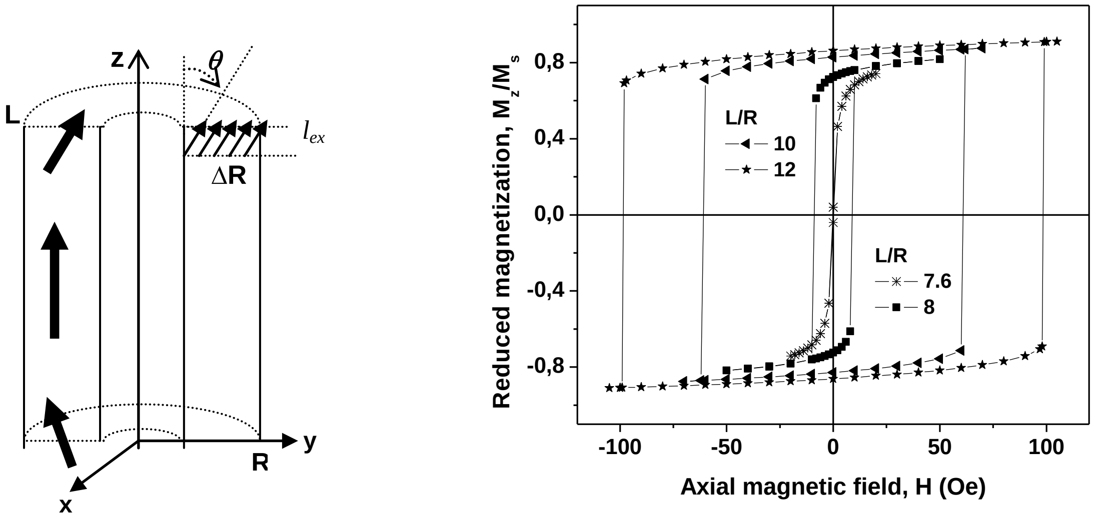

Fig. 1. Schematic representation of magnetization distribution in a nanotube (left). Hysteresis loops (right) of the C-state nanotubes of thickness ΔR=20 nm and radius R= 50 nm in the axial magnetic field for the different tube aspect ratios, L/R. $K_u = 10^5$ erg/cm^3.

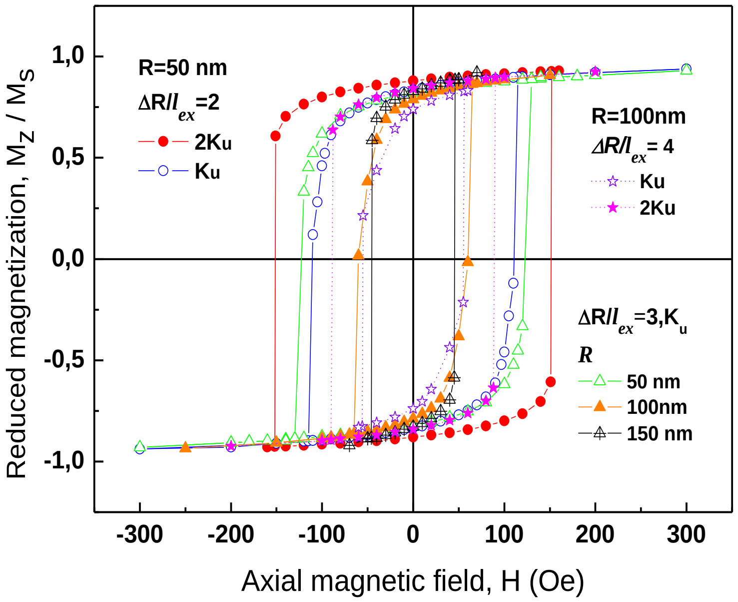

Fig.2. Hysteresis loops of the B-state nanotubes. The tube aspect ratio L/R=20. Geometrical parameters of the nanotubes: R=50 nm, $\Delta R/l_{ex}$ =2; R=100 nm, $\Delta R/l_{ex}$= 4; and $\Delta R/l_{ex}$ = 3, R= 50 nm, 100 nm, 150 nm, respectively. The anisotropy constant is K_u =5x10^4 erg/cm^3.