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Domain-wall-assisted giant magnetoimpedance of thin-wall ferromagnetic nanotubes

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ABSTRACT

We study the efficiency of the magnetoimpedance (MI) of thin-walled circumferentially-ordered nanotubes in sub-GHz and GHz frequency regimes, using micromagnetic simulations. We consider empty ferromagnetic tubes as well as tubes filled with non-magnetic conductors of circular cross-section (nanowire coverings), focusing on the low-field regime of MI (below a characteristic field of the low-frequency ferromagnetic resonance). In this field area, the efficient mechanism of MI is related to oscillations of the positions of (perpendicular to the tube axis) domain walls (DWs). Two mechanisms of driving the DW motion with the AC current are taken into account; the driving via the Oersted field and via the spin-transfer torque. The simulations are performed for Co nanotubes of the diameter of 300 nm. Achievable low-field MI exceeds 100%, while the field region of a high sensitivity of that DW-based giant MI is of the width of tens of kA/m. The later is widely adjustable with changing the density of the driving AC current, its frequency, and the nanotube length. Of particular interest is the resonant motion of DW due to the interaction with the nanotube ends, the conditions of whom are discussed.

1. Introduction

The giant magnetoimpedance (GMI) is utilized in sensing weak magnetic fields (e.g. Oersted fields, geomagnetic fields, stray fields, etc.) with a very large field sensitivity (compared to the one achievable with the giant magnetoresistance or the Hall effect) while with low requirements on working conditions of the sensor (contrary to the SQUID magnetometers) [1–4]. Though, magnetic systems of different geometries are considered to be active ingredients of the GMI-based sensors, the conducting ferromagnetic cylinder (the ferromagnetic wire) and the tube are base systems when building mathematical models of GMI. Within these two, the tube geometry is attractive because it allows for better isolating different mechanisms of the magnetoimpedance (MI) than a magnetic wire. The wires that reveal the GMI (e.g. amorphous magnetic microwires with negative constant of the volume magnetostriction) are of a complex magnetic structure, with an axially-magnetized inner core and a circumferentially-magnetized outer shell, whereas, the inner core is absent in the tube. This removes one of the basic mechanisms of the (middle-frequency) MI of the wires which is based on the dependence of the inner-core radius on the external axial field, (the operating frequency for that MI mechanism is limited by the skin effect). In the low-frequency range, that mechanism of MI of the magnetic wire coexists with an impedance-inducing oscillatory motion of the domain walls (DWs) in the other shell. In order to isolate the later (low-frequency) mechanism of MI, one has proposed to use a conductive non-magnetic microwire covered with a tubular ferromagnetic layer. An advantage of the tube geometry with regard to the high-frequency MI, whose mechanism is based on the ferromagnetic resonance (FMR), follows from a magnetic softening of the tubes relative to the wires [5], (in the microwires, the magnetostatic core–shell interaction can be strong, especially, in the case of the circumferential ordering of the outer shell [6]).

Though, the middle- (skin-effect-based) and high-frequency (FMR-based) GMI of the soft-magnetic microwires and microtubes are very-well-described and optimized effects, (the thresholds are typically in sub-MHz and sub-GHz ranges), DW-based MI is not explored in detail. A huge limitation of its efficiency in the micro-sized systems follows from the damping of the Oersted-field-driven motion of the DW by eddy currents which this motion induces [7,8]. The damping is expected to strengthen with the driving-current frequency, while its details are under debate, (note that performing full micromagnetic simulations of the microwires/microtubes remains to be a challenge), [9–11]. In the nanotubes of the wall thickness comparable to the electronic mean free path, such eddy currents are expected to be suppressed. Recent development of the techniques of the nanowire and nanopore coating (atomic-layer deposition, electroplating) and rolling up the nanomembranes allows for creating the tubes of extremely small thickness of the wall, whose domain structures are stable in wide ranges of external

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conditions [12–17]. Via adjusting parameters of the manufacturing process (oblique-evaporation and thermal treatment, [18,19]) and material composition [20], the magnetic anisotropy can be largely tuned allowing for stabilization of the circumferential ordering in the nanotube. Such an ordering is crucial for GMI, however, it has also attracted an attention with regard to creating a racetrack memory with a reduced (compared to the nanowires) stray field of (densely packed) DWs [17]. Our study of the nanotubes is motivated by the idea of GMI-based sensing with a nm-sized spatial resolution [21].

There is a small number of reports on GMI of the magnetic nanosystems with flux-closure geometries (e.g. multi-segmented; "barcode" nanowires [22], multilayers with closed magnetic path [23], nanotubes [24]), whereas, a comparative study shows that property of the nanosystem to be desired for optimizing MI above some (relatively-low) threshold frequency of the current [25]. While the mechanism of GMI in the barcode nanowires relates to the magnetization rotation in their whole volume, the DW motion plays a role in the low-field MI of the flux-closure multilayers whose generic model is the nanotube. Note that scaling the soft-ferromagnetic microwires down to the nm-sizes leads to their magnetostatically-induced hardening; vanishing the circumferentially-magnetized outer-shell. In the consequence, MI of the magnetic nanowires is weak [26], while the nanotube remains the simplest high-symmetry system for studying DW-based GMI at the nanoscale.

In the present paper, with micromagnetic simulations, we study the dynamical response of the magnetic subsystems of DW-containing Co nanotubes to the AC current, in the presence of a constant axial magnetic field. We consider a tubular covering of a conducting nanowire as well as an empty nanotube (Fig. 1). The tubes are of a strong easy-plane anisotropy (the circumferential ordering) and we pay especial attention to the low-field regime, thus, focusing on the effects of the DW motion. The time dependence of the average circumferential component of the magnetization is analyzed with dependence on the current parameters (density amplitude, frequency) and the field and on the nanotube length, while details of the corresponding magnetization dynamics are monitored. We establish operating regimes of nanotube GMI.

Upon introducing a model of the magnetic nanotube dynamics in Section 1, in Section 2, we present the results of the micromagnetic simulations of Co nanotubes under the electrical AC current. Conclusions are formulated in Section 4.

2. Model

2.1. Equation of motion

Our micromagnetic model of a thin-wall nanotube is a reduced version of a model formulated in [27]. Its magnetization evolves according to the Landau-Lifshitz-Gilbert (LLG) equation in 3D that takes the form

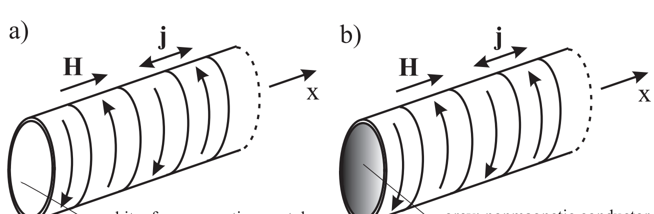

Fig. 1. Schemes of the systems studied; the empty ferromagnetic nanotube (a), the magnetic covering of a nonmagnetic conducting wire (b), including the bamboo-like magnetic structure of circumferentially-ordered domains (the curved arrows indicate the magnetization), and indicating the direction of the external field and the electrical-AC flow.

$$-\frac{\partial \mathbf{m}}{\partial t} = \frac{2\gamma A_{ex}}{M_s^2}\mathbf{m}\times\Delta\mathbf{m} + \gamma\mathbf{m}\times(\mathbf{B}_{ms}+\mathbf{B}_{Oe}+\mathbf{B}) - \frac{\eta j}{M_s^2}\mathbf{m}\times\left(\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial x} + \beta M_s\frac{\partial \mathbf{m}}{\partial x}\right) + \frac{2\gamma K}{M_s^2}(\mathbf{m}\cdot\hat{\imath})\mathbf{m}\times\hat{\imath} - \frac{\alpha}{M_s}\mathbf{m}\times\frac{\partial \mathbf{m}}{\partial t}. \quad (1)$$

Here, $\hat{\imath} \equiv [1, 0, 0]$, (the wire is directed along the x axis), $M_s = |\mathbf{m}|$ represents the saturation magnetization, A_{ex} denotes the exchange stiffness, γ – the gyromagnetic factor), K determines the strength of the effective axial anisotropy (specified in the next paragraph), α - the Gilbert damping constant. The magnetostatic and external fields are denoted by $\mathbf{B}_{ms}$ and $\mathbf{B}$, respectively. The presence of the electric current of the density j (that flows along the nanotube) is included via the Oersted-field ($\mathbf{B}_{Oe}$) term on the right-hand side of (1) and via the spin-transfer torque (STT); whose coupling constant $\eta = Pg\mu_B/2eM_s$ is dependent on the spin polarization of the system P, the Lande factor g, the Bohr magneton μ_B, and the absolute value of the electron charge e. The unitless parameter β determines the strength of the non-adiabatic STT. Since there is no commonly-accepted methodology for measuring β, [28], we follow a (structure-stability-based) reasoning of [29] that leads to $\beta \approx \alpha$. Let us note that performing micromagnetic simulations with the simplified (Landau-Lifshitz) form of the LLG equation requires rescaling the input parameter $\beta \to 2\beta$.

Here, we restrict our considerations to the circumferentially-magnetized tubes, which requires the axial-anisotropy constant K to be negative and dominate over the shape anisotropy of the magnetostatic origin. The main contributions to the anisotropy have been described in [27] to relate to the internal stress of the tube that is dependent on the manufacturing method. With relevance to the thin-wall microtubes, we have specified two basic regimes of the anisotropy which correspond to a solidification-dominated stress and a cooling-dominated stress. The later drives the circumferential ordering in the tube (wire) made of a material with a negative constant of the volume magnetostriction. The former can be induced by specifying the direction of the material deposition when forming the tube-shaped magnetic layer (via a "shadowing" effect, i.e. the creation of a crystallographic texture, and/or interface steps) [18,19]. In the tubes of ultimately-thin walls, such a solidification-induced anisotropy is expected to determine the ordering direction.

The (circumferential) Oersted field is dependent on the radial coordinate of the tube $\rho \equiv \sqrt{y^2+z^2}$, [let the angular coordinate be $\varphi \equiv \arctan(z/y)$]. In the case of the empty nanotube, assuming the current density to be uniform, via the Ampere's law, one finds the circumferential field (the transverse component of the field) $H_\varphi(\rho, t) = -j(t)(\rho^2 - R_{in}^2)/2\rho$, where $R_{in(out)}$ denotes the inner (outer) radius of the tube. When the tube is considered as a covering of a circular nanowire, the Oersted field is taken in the form $H_\varphi(\rho, t) \approx \overline{H}_\varphi(t) = -j(t)\overline{R}/2$, with $\overline{R} = (R_{in} + R_{out})/2$. Averaging the Oersted field over the radial coordinate of the tube is performed following $\overline{H}_\varphi = (R_{out} - R_{in})^{-1}\int_{R_{in}}^{R_{out}} H_\varphi(\rho, t)\mathrm{d}\rho$. For a given value of the current density, the Oersted field in the covering of the nanoconductor is considerably (several times) higher than for the case of the empty nanotube, whereas, the STT amplitude is independent of the tube filling.

2.2. Dynamical regimes

The MI of thin-wall nanotubes is expected to follow from the DW motion for up to GHz frequencies of the current, whereas, the importance of the DW motion for the microwire or microtube GMI is believed to be restricted to a low-frequency (kHz) regime [30,31]. We perform a simple estimation of the upper frequency limit of DW-based MI, noticing that the second of two basic mechanisms of GMI in the nanotube (a high-frequency one) relates to exciting FMR. Considering sufficiently low axial fields ($H_x \ll M_s$), we claim the frequency of the