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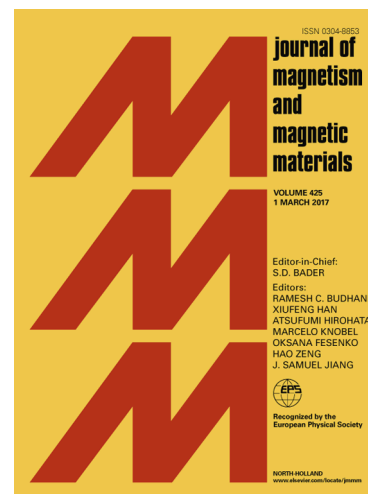
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Exchange bias effect in cylindrical nanowires with ferromagnetic core and polycrystalline antiferromagnetic shell

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Abstract

We study numerically the exchange bias effect in thin cylindrical nanowires composed of a ferromagnetic core and an antiferromagnetic shell implementing a classical spin Hamiltonian and Monte Carlo simulations. We address systematically the effect of shell polycrystallinity on the characteristic fields of the isothermal hysteresis loop (coercivity, exchange-bias) and their angular dependence upon the direction of the reversing and cooling fields. We relate the observed trends to modifications of the underlying magnetization reversal mechanism. We fit our simulation results to an extended Stoner-Wohlfarth model with effective off-axis unidirectional anisotropy and demonstrate that shell polycrystallinity leads to maximum exchange bias effect in an off-axis direction. Our results are in qualitative agreement with recent experimental studies of Co/CoO nanowires.

Keywords: exchange bias, core-shell nanowires, effective anisotropy, Monte Carlo.

PACS: 75.60.Jk, 75.75.Jn, 75.75.Fk, 75.78.Fg

Highlights

- Exchange bias in Co/CoO core-shell nanowires
- Effect of shell polycrystallinity on magnetization reversal
- Angular dependent exchange bias effect
- SW model and effective anisotropy

1. Introduction

Tailoring the magnetic properties at the nanoscale currently gathers a major research effort due to the plethora of new phenomena and their prospective technological applications[1]. In particular, advances in template-assisted

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electrodeposition[2, 3] and solution chemistry methods[4, 5] have greatly facilitated the growth and study of quasi-one dimensional magnetic nanostructures, such as nanowires and nanotubes. These systems are characterized by enhanced shape anisotropy of magnetostatic origin, which renders them prominent candidate materials for advanced technologies ranging from magnetic recording[6] to biomedicine[7, 8]. On the other hand, their quasi-one dimensional geometry is ideal for efficient manipulation of magnetic solitonic excitations, such as domain walls, with potential applications to 3D magnetic memory[9]. The magnetization reversal process is a central issue of the research related to magnetic nanowires and nanotubes. Their quasi one-dimensional shape leads to a complex reversal mechanism, consisted of domain wall (DW) nucleation, propagation and annihilation[2, 6, 10]. Furthermore, it has been demonstrated that the magnetic anisotropy of nanowires and the concomitant magnetization reversal mechanism can be tailored by homogeneous alloying [11], by periodic chemical modulation [12] and by periodic morphological modulation, as in diameter-modulated nanowires[13].

A promising alternative route to tailor made magnetic anisotropy of nanostructures is offered by the exchange bias (EB) effect[14, 15] that has been extensively studied in exchange-coupled nanostructures with a ferromagnetic (FM) core - antiferromagnetic (AF) shell morphology[16, 17]. Hysteresis loops of such systems exhibit a characteristic shift after been field-cooled, usually accompanied by magnetic hardening. Materials presenting these properties are currently implemented in spintronics applications, like spin-valves and magnetic tunnel junctions[18]. Elongated nanostructures with FM core - AF shell morphology such as nanowires[19, 20, 21] and nanotubes[22, 23] have been studied less, however these structures also showed exchange-bias and the accompanying effects. Most interestingly, magnetic FM-AF core-shell nanowires offer an ideal test-bed to study the competition between shape and unidirectional anisotropies, the latter been induced by a field-cooling process. Salazar-Alvarez et al[24] demonstrated the possibility to manipulate the high field magnetization in surface oxidized cobalt nanowires in the the normal to the wire axis direction, using the exchange-bias effect. In a search for optimum applied field direction for enhancement of the EB effect, Tripathy *et al*[20] investigated the angular dependence of the EB field of lithographically grown Co/CoO nanowires and demonstrated the increase of the EB field in off-axis directions. Gandha *et al*[21] reported giant EB effect in chemically-grown Co/CoO nanowires and further enhancement of the EB effect in an off-axis direction relative to the nanowire axis. The competition between anisotropies of different strength and symmetry has been theoretically investigated within the coherent rotation model of Stoner-Wohlfarth[25, 26] and discontinuous jumps of the exchange bias field and the coercivity were predicted at specific angles related to the internal easy axis.

Due to the crucial role played by the FM-AF interface spin structure in the EB effect[16] a realistic description of the structure and dynamics of the AF layer that goes beyond the coherent rotation model is required. In a previous work[27], we studied numerically the exchange bias effect in monocrystalline Co/CoO nanowires and showed the suppression of the coercivity due to the presence of the monocrystal CoO shell that acts as a sequence of nucleation centers for magnetization reversal[27, 19]. However, Co/CoO nanowires prepared by controlled surface oxidation of chemically synthesized cobalt nanowires develop a polycrystalline shell[21], which is anticipated to modify the shell magnetization dynamics and the reversal mechanism of the core. The effect of shell granularity in Co/CoO bilayers

has been recently studied experimentally[28] and it was shown to cause enhancement of the EB field. However, to the best of our knowledge, the issue of the effect of shell granularity on the the coercivity, the EB field and their angular dependence in the case of FM-AF core-shell nanowires has not been addressed yet.

In the present work, we implement the Monte Carlo method to study the effects of shell granularity on the EB behavior of cylindrical nanowires composed of a monocrystalline Co core and polycrystalline CoO shell. Shell granularity is shown to soften the magnetic anisotropy of the shell leading to enhancement of coercivity and suppression of the EB field. Additionally, shell granularity is shown to produce a monotonous drop of the coercive field and a non-monotonous drop of the EB field. The appearance of an optimum EB value is interpreted as an effective off-axis uniaxial anisotropy in the framework of a mesoscopic Stoner-Wohlfarth (SW) model[29]. Finally, a comparison is made between our model predictions and recently reported measurements of the EB effect in Co/CoO nanowires[21].

2. Model and Simulation Method

Nanowires are generated by cutting a cylinder along the z-axis with radius R and length L from an auxiliary simple cubic lattice with constant a . For the core-shell morphology we define an internal homoaxial cylinder with radius $R_c = R - t$ and length $L_c = L - t$, where t is the shell thickness. We approximate the shell polycrystallinity (granularity) by dividing the shell in N_z cylindrical slices along the z-axis and each slice in N_ϕ circular sectors. Thus, the shell is divided in $N_g = N_z N_\phi$ identical crystallites (grains) with width $w_g = L/N_z$, as seen in Fig. 1. The total energy of the magnetic system is $E = \sum_i E_i$, where the single-site energy term reads

$$E_i = -\frac{1}{2} \hat{S}_i \cdot \sum_{\langle j \rangle} J_{ij} \hat{S}_j - K_i (\hat{S}_i \cdot \hat{e}_i)^2 - H (\hat{S}_i \cdot \hat{H}) - \frac{1}{2} g \hat{S}_i \cdot \sum_j \mathbf{D}_{ij} \cdot \hat{S}_j. \quad (1)$$

In Eq. 1, hats indicate unit vectors and bold symbols 3×3 matrices in Cartesian coordinates. The $1/2$ prefactor in the first and fourth terms in Eq. 1 accounts for the double-counting of the energy contribution from each site-pair (bond). The first term in Eq. 1 is the exchange energy between first nearest neighbors (1nn) sites. The exchange constant J_{ij} takes the values J_{FM} , J_{AF} and J_{int} depending on whether sites i and j belong to the FM, the AF or the interface region, respectively. The latter contains the sites of the core (shell) having exchange bonds with sites in the shell (core). For 1nn exchange couplings, the interface region has width $2a$ and consists of the core-interface layer and the shell-interface layer. The second term in Eq. 1 is the uniaxial anisotropy energy. The easy axes $\hat{e}_i$ of the core sites are taken along the cylinder axis. Shell sites belonging to the same grain have a common easy axis, which, however, varies at random between different grains. The anisotropy constant K_i takes the values K_{FM} and K_{AF} depending on the location of site i . The third term in Eq. 1 is the Zeeman energy due to the applied field H and the fourth term is the dipolar energy with strength g . For computational efficiency, the dipolar energy term is treated in an embedded cluster approximation with a cluster radius $r_0 = 3a$ [27].

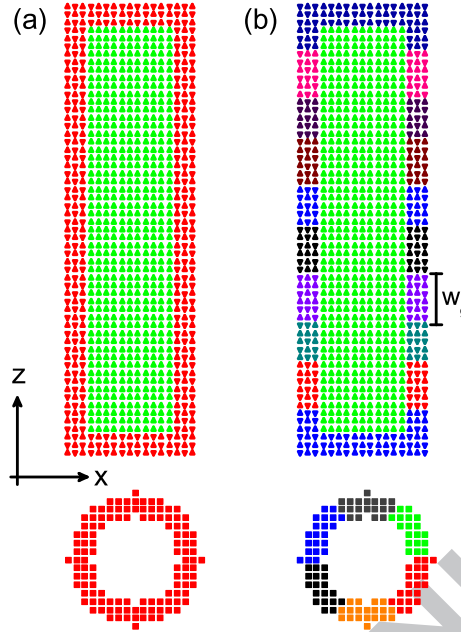


Figure 1: (Color online) Cutting planes (top) and shell cross sections (bottom) of cylindrical core/shell nanowires with $R_c = 5a$, $L_c = 50a$ and $t_{sh} = 3a$. The nanowire shell is (a) monocrystalline and (b) polycrystalline with $N_g = 60$ ($N_z = 10$, $N_\phi = 6$) grains of width $w_g \approx 5.6a$.

To observe the EB effect the nanowires are field-cooled (FC) from a high temperature ($T \gg T_c$) to a low temperature ($T \ll T_N$) under a field well below the saturation value of the AF phase ($H_{cool} \ll H_{sat}$). At the end of the FC process the external field is swept ($-H_{cool} \leq H \leq +H_{cool}$) at a constant rate to obtain the isothermal hysteresis loop. The effective coercivity of the system is then defined as $H_c = |H_{c1} - H_{c2}|/2$ and the EB field as $H_{eb} = |H_{c1} + H_{c2}|/2$, where H_{c1} and H_{c2} are the coercive fields corresponding to the descending (ie. against the cooling field direction) and the ascending branch of the loop, respectively.

The FC process is simulated using the Metropolis Monte Carlo algorithm with single-spin updates and a temperature-dependent spin-cone aperture that accelerates the approach to equilibrium[30]. The isothermal hysteresis is simulated using the same algorithm, but with a fixed spin-cone aperture ($\theta_s \approx 3^\circ$). Thermal relaxation at each (H, T) -point is done with $5 \cdot 10^3$ Monte Carlo steps per spin (MCSS) for thermalization followed by 10^4 MCSS for calculations of thermodynamic quantities. The latter are calculated every 10 MCSS to minimize statistical correlations of the sampling points. The results at each (H, T) -point are averaged over 20 – 40 independent relaxation sequences. For systems with structural disorder, as the nanowires with granular shells, an average over 30 – 50 samples with different realizations of disorder is performed.

In Eq. 1 we use dimensionless energy parameters scaled by J_{FM} , which is arbitrarily taken as $J_{FM} = 10$, and $J_{AF}/J_{FM} = -0.5$, $J_{int}/J_{FM} = -0.5$, $K_{FM}/J_{FM} = 0.1$, $K_{AF}/J_{FM} = 1.0$ and $g = 0.05/J_{FM}$. These

parameters capture the main features of the Co/CoO exchange coupled system as previous studies of oxide-coated cobalt nanoparticles [17, 31] and nanowires[27] have shown. Temperature T and the magnetic field strength H are measured in units of J_{FM} . Field-cooling is performed from high temperature $T_H = 2.00J_{FM}$ to low temperature $T_L = 0.01J_{FM}$ under an applied field $H = 4.0J_{FM}$ with constant cooling rate $r_T = 10^{-5}J_{FM}/\text{MCSS}$. The field sweep rate is also kept constant at $r_H = 10^{-5}J_{FM}/\text{MCSS}$ to exclude variation of results with sampling time.

3. Results and Discussion

3.1. Isothermal hysteresis loops

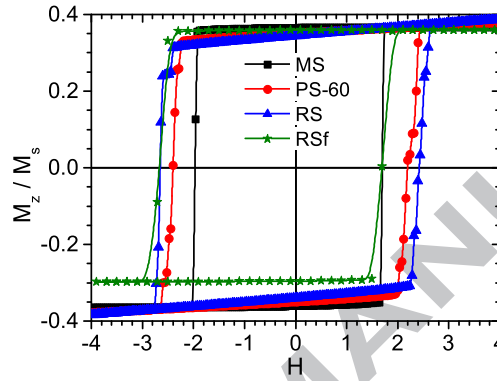


Figure 2: (Color online) Isothermal hysteresis loops of FM/AF nanowires of the same nominal size and different number of shell grains. Squares (black): monocrystalline shell ($N_g = 1$). Circles (red): polycrystalline shell ($N_g = 60$). Triangles (blue): random shell ($N_g = 7098$). Stars (green): random frozen shell. Other parameters as in Table 1.

We study first the macroscopic magnetic behavior of the nanowires, by calculating the low-temperature hysteresis loops and the characteristic fields of the loop, namely the coercivity (H_c) and the exchange-bias (H_{eb}), when the cooling and reversing fields are applied along the cylinder axis (z-axis). Different structural models of the AF shell are considered, as summarized in Table 1. In the limiting case of a monocrystalline shell (MS) a single shell grain ($N_g = 1$) exists, while in the other extreme case of a random shell (RS) each shell grain contains a single site ($N_g = 7098$). In the intermediate case of a polycrystalline shell (PS-60), the shell contains ($N_g = 60$) grains. Correspondingly, the size of the shell grains is maximum in the monocrystalline sample and minimum in the random sample.

In Fig. 2 we compare the loops of nanowires with the same length, diameter and shell thickness, but different degree of shell crystallinity. The loop of a random shell with frozen spins (RSf) during field sweep is also included. A clear horizontal shift of the loops is observed in all samples as the outcome of the FC process. An overall feature seen is the gradual shearing of the loop as the size of the grains decreases, which is related to the fact that in nanowires with many grains and many easy axes in the shell, there exists a wider distribution of energy barriers to the reversal

Table 1: Structural parameters and results for core-shell nanowires with $R_c = 5a$, $L_c = 50a$ and $t_{sh} = 3a$.

System	$w_g/a^{(1)}$	H_c	H_{eb}	$M_{AF,int}^{(2)}$	$\mu^{(3)}$
MS ^a	56.0	1.82	-0.14	0.015	0.0140
PS-60 ^b	5.6	2.30	-0.11	0.052	0.0120
RS ^c	1.0	2.54	-0.10	0.054	0.0085
RSf ^d	1.0	2.18	-0.49	0.054	0.0099

⁽¹⁾ shell grain size⁽²⁾ shell-interface magnetization (per spin) at the FC state⁽³⁾ domain wall mobility (a/MCSS)^a monocrystalline shell^b polycrystalline shell with $N_g = 60$ grains^c random shell ($N_g = 7098$)^d random shell with frozen spins during field sweep.

of the core interface moments. Furthermore, it becomes clear by simple inspection of Fig. 2 that the loops widen while their shift decreases with decreasing grain size, which directly implies an increase of coercivity and decrease of the exchange-bias field in nanowires with small grains. Our numerical results for H_c and H_{eb} for different structural models used in the present work are summarized in Table 1.

The physical origin of the observed dependence of H_c and H_{eb} on the grain size can be attributed to two distinct physical factors, namely the response of the shell-interface magnetization ($M_{AF,int}$) to the applied field and the actual value of $M_{AF,int}$ at the FC state.

To explain this point further, we show first in Fig. 3 the magnetization of the shell-interface layer as the applied field is swept. The observed expansion of the hysteresis loop with decreasing grain size indicates that the shell-interface spins are dragged by the core spins, via their mutual exchange coupling (J_{int}). The magnetization drag mechanism becomes more efficient as the size of the grains decreases. The exclusive impact of the drag mechanism on H_c and H_{eb} can be deduced by comparison of the RS and the RSf nanowires that have identical AF spin structures at the FC state (i.e. $M_{AF,int}$ values), but for the latter the shell moments are held frozen in their FC directions during the field sweep. As seen in Table 1 for these nanowires, H_c is suppressed and H_{eb} is dramatically enhanced when the magnetization drag is switched off.

Second, the role of $M_{AF,int}$ is revealed if one compares the MS and RSf nanowires, that have very different FC states (see Fig. 4), however, for both these systems the shell-interface moments remain frozen during field sweep. In the case of the MS nanowire, freezing of the shell-interface moments is dictated by the strong uniaxial anisotropy of the AF shell, as can be deduced from the insensitivity of shell magnetization to the applied field (Fig. 3). For RSf nanowires the shell moments are kept frozen during the simulation. The relative data in Table 1 show increased value of $M_{AF,int}$ for the RSf system which is accompanied by enhancement of both H_c and H_{eb} . We mention that this

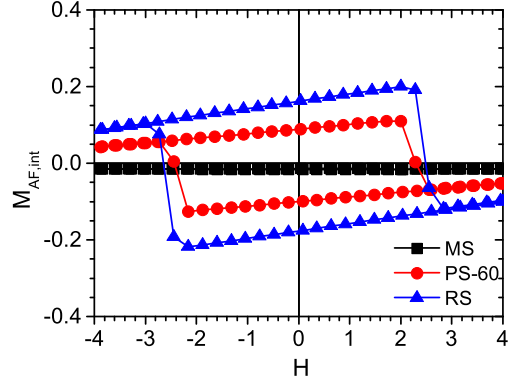


Figure 3: (Color online) Isothermal hysteresis loop of the shell interface layer, showing enhancement of AF drag effect with decreasing shell grain size. Structural parameters as in Table 1.

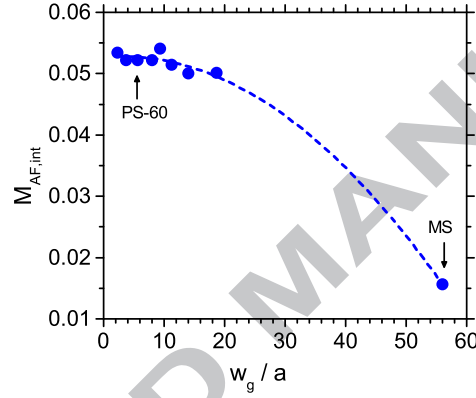


Figure 4: Dependence of the shell interface magnetization at the FC state on the shell grain size. Dashed line is a guide to the eye. Structural parameters as in Table 1.

result is in accordance to the predictions of the Meiklejohn-Bean model that the bias-field varies linearly with the AF moment[32]. Overall, we conclude that the AF magnetization drag effect and the net interface moment of the AF shell $M_{AF,int}$ act in synergy to enhance H_c , while they act in competition to suppress H_{eb} .

In Fig. 5 we show the dependence of the characteristic fields on grain size. In all cases the central angle of the grains is kept constant ($\phi \approx 60^\circ$) and only the width of the grains varies. We consider this is a reasonable approximation, because the nanowires studied here are thin and support transverse walls with almost coherent in-plane spin structure[27]. Thus, further reduction of the grain angle, leading to increase of N_ϕ values, did not modify our results. A systematic trend is seen in all cases, namely as the grain size is reduced, H_c increases and H_{eb} decreases. This trend can be understood in the framework of the random anisotropy model[33], where reduction of the grain size leads to an effective anisotropy of the AF shell that is an average value over several grains within the range of the exchange correlation length and thus reduced in magnitude. The gradual magnetic "softening" of the AF shell with

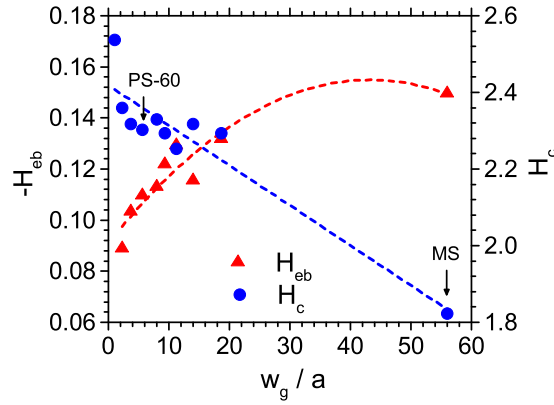


Figure 5: (Color online) Dependence of coercivity and exchange bias field on shell grain size. Dashed lines are guides to the eye. Structural parameters as in Table 1.

decreasing grain size, enhances the magnetization drag of the interface moments and cases the observed behavior of H_c and H_{eb} .

3.2. Magnetization reversal mechanism

We discuss next, the impact of shell polycrystallinity on the underlying magnetization reversal mechanism. It is well established that magnetization reversal in FM nanowires proceeds by propagation and annihilation of a pair of domain walls that nucleate at the two free ends of the nanowire [2, 34, 35]. The coupling to an AF shell modifies the reversal mechanism, as previous experimental[19] and numerical works have demonstrated[19, 27]. In FM/AF nanowires with a monocrystalline shell, the unsatisfied bonds at the interface act as nucleation centers of a secondary magnetization reversal mechanism, which in synergy to the domain wall propagation accelerate the reversal of the core magnetization[27]. This behavior is seen in Fig. 6a as a lowering of the core magnetization in the central region between the two domain walls. As one can readily observe in Fig. 6, this secondary mechanism is absent in the PS and the RS nanowires, where reversal proceeds by clear domain wall propagation. The reason for disappearance of the secondary mechanism is the effective magnetic softening of the shell magnetization in the PS and RS nanowires, which no longer acts as a collection of nucleation centers for magnetization reversal. The magnetic softening of the shell interface magnetization results in lower domain wall velocities in the core, as seen in Fig. 7 and also by comparison of domain wall mobility values for the MS, PS and RS nanowires in Table 1. The contribution of the shell-interface magnetization $M_{AF,int}$ in the modification of the wall velocities and mobility can be also deduced from Fig.7. The RSf nanowire that has higher $M_{AF,int}$ value than the MS nanowire (see Fig. 4), exhibits a lower mobility. On a microscopic level, this trend is explained as the number of satisfied interface bonds is substantially higher for the RSf nanowire. These bonds being in their lowest energy state oppose their reversal under the applied field, acting as soft pinning centers for domain wall propagation.

Thus, drag of the AF interface moments and increased $M_{AF,int}$ magnitude due to polycrystallinity are the two

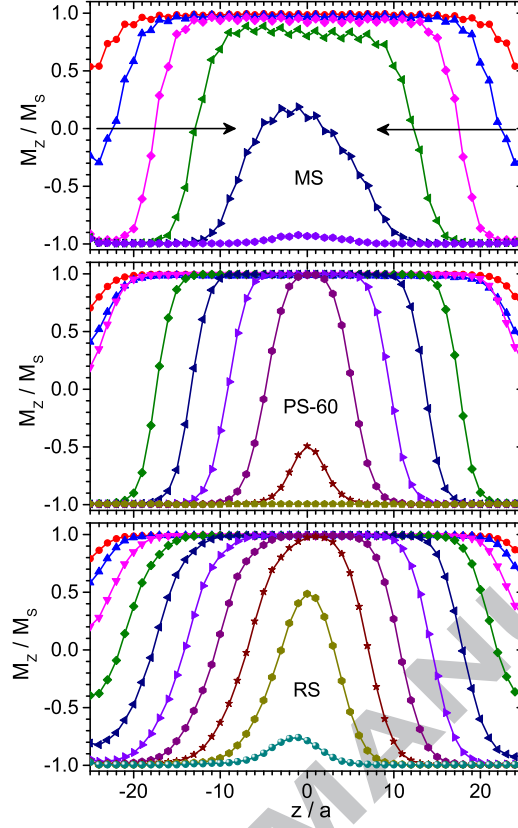


Figure 6: (Color online) Time-evolution of magnetization profile under application of a reverse field $H = -4.0$ of nanowires with different shell granularity. Snapshots are taken every $\Delta t = 200$ MCSS starting at $t_0 = 200$ MCSS. Horizontal arrows indicate the propagation direction of the domain walls. Structural parameters as in Table 1.

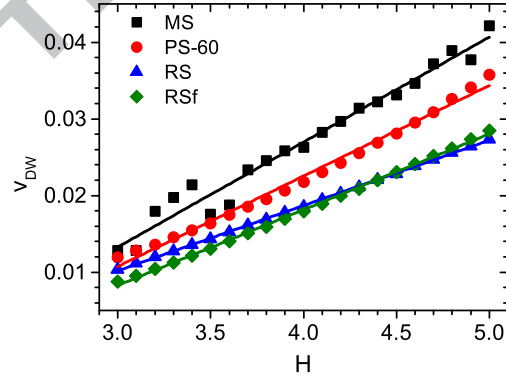


Figure 7: (Color online) Field-dependence of DW velocity in nanowires with different shell granularity. Straight lines are linear fit to the data showing a drop of the DW mobility (slope) with increasing shell granularity. Mobility values are reported in Table 1. Structural parameters as in Table 1.

factors acting in synergy to suppress the domain wall mobility in polycrystalline samples. A systematic decrease of wall mobility with decreasing grain size is shown in Fig. 8.

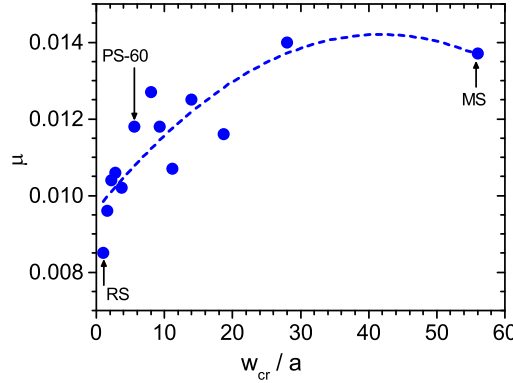


Figure 8: (Color online) Dependence of DW mobility on shell grain size. Arrows indicate the structural models reported in Table 1. Dashed line is a guide to the eye. Other parameters as in Table 1.

3.3. Angular dependence of H_c and H_{eb}

In the present section, we study the changes introduced in the hysteresis behavior of core-shell nanowires, when the cooling field and the reversing field both lie at an angle ϕ_H with respect to the nanowire axis. In Fig. 9 we show the angular dependence of the hysteresis loop for samples with monocrystalline and polycrystalline shells.

As the field angle relative to the nanowire axis increases, a gradual shrinking and tilting of the loop is observed, as both the crystallographic and shape anisotropies lie along the nanowire axis. Shell granularity does not change this trend. Analysis of the hysteresis loops at different field angles provides the angular dependence of the coercivity and EB shown in Fig. 10. A monotonous decrease of H_c with field angle is seen for monocrystalline and granular samples. However, the polycrystalline and random samples exhibit higher coercivity values than the monocrystalline sample at all angles. This behavior is due to AF drag effect, discussed previously (see Fig. 4).

A more complex behavior is seen in Fig. 10b in the angular dependence of H_{eb} . In particular, the monocrystalline nanowire exhibits a weak increase of H_{eb} at small angles with a broad peak around $\phi_b \approx 10^\circ$. This peak is attributed to the competition between two distinct factors, namely, the susceptibility of the AF shell and the projection of the bias field on the applied field direction. First, we mention that the AF shell of the MS nanowire is a hard antiferromagnet with anisotropy along the z-axis. So, the susceptibility of the shell increases when the field angle changes from the parallel to the normal direction and consequently, the shell interface magnetization ($M_{AF,int}$) increases too when the cooling field rotates with respect to the z-axis. Indeed, a linear fit $M_{AF,int} \sim M_0 + \lambda\phi_b$, is seen in Fig. 10c. Second, for fixed shell interface magnetization, the bias field decreases as $H_{eb} \sim \cos\phi_H$ according to the Meiklejohn-Bean description of the EB effect[32]. Thus, an overall dependence $H_{eb} \sim (M_0 + \lambda\phi_H) \cdot \cos(\phi_H)$ is expected for the MS nanowire, which is characterized by an optimum field angle for maximum H_{eb} values. The optimum angle is

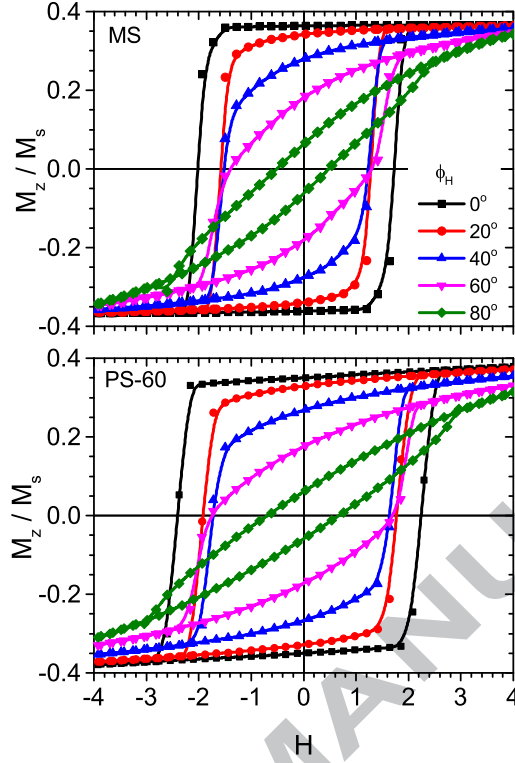


Figure 9: (Color online) Angular dependence of hysteresis loops of nanowires with monocrystalline shell (upper panel) and polycrystalline shell (lower panel). Parameters as in Table 1.

$\phi_{max} \sim 10^\circ$ within our model for the MS nanowire. When shell granularity is present, as in PS and RS nanowires, the shell becomes magnetically softer and the H_{eb} values drop. Furthermore, due to the random distribution of the easy axes of the shell grains, the susceptibility of the AF shell becomes isotropic and the broad peak of H_{eb} at $\sim 10^\circ$ vanishes. However, a sharp but weak increase of H_{eb} is seen for the polycrystalline sample for slightly off-axis directions. This behavior, despite being weak within our model is well understood within an effective SW model to be discussed next.

3.4. Effective Stoner Wohlfarth model

In this section, we fit our simulation results to an effective SW model. We define the SW model in dimensionless units, as follows:

$$e(\phi) = -\frac{1}{2} \cdot k \cdot \cos^2(\phi) - h \cdot \cos(\phi - \phi_H) - h_b \cdot \cos(\phi - \phi_b) - \frac{1}{2} \cdot k_R \cdot \cos^2(\phi - \phi_H) \quad (2)$$

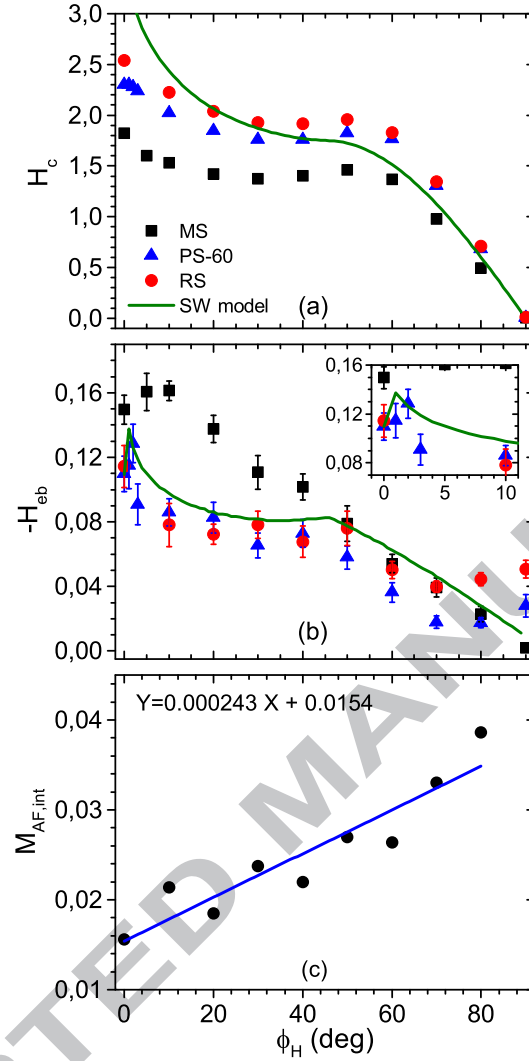


Figure 10: (Color online) Angular dependence of (a) coercivity and (b) exchange bias field for different structural models described in Table 1. The solid line is a Stoner-Wohlfarth model fitted to the simulated data with parameters $k = 3.5$, $k_R = 0.2$ and $h_b = 0.11$ and $\phi_b = 5^\circ$. Error bars, when not indicated, are of the size of the marks. Inset to (b) is the enlarged angular region around the sharp peak of H_{eb} for the polycrystalline sample. (c) Linear dependence of the AF-interface magnetization ($M_{AF,int}$) of the monocrystalline nanowire (MS) on the angle of the applied field.

where k is the anisotropy of the FM assumed along the z-axis, h is the applied field at an angle ϕ_H , h_b the bias field at an angle ϕ_b and k_R is an effective anisotropy that accounts for the coercivity enhancement due to drag of the AF interface moments[29]. We obtain the values of the dimensionless parameters in Eq. 2 from the simulation results (Fig. 10), as follows[29]: $k_R = \frac{1}{2} H_c^{(mc)} / K_{FM}^{(mc)} - 1 \approx 0.2$ and $h_b = H_{eb}^{(mc)} \approx 0.11$, where the superscript (mc) denotes values related to our Monte Carlo simulations. The anisotropy k is not fitted to the coercivity value[29], but

is treated as an adjustable parameter. This is because the coherent rotation mechanism, inherent to the SW model, overestimates the coercivity for an applied field along the easy axis. The angle ϕ_b is also treated as an adjustable parameter. We perform numerical minimization of Eq. 2, leading for each h value to one (reversible part) or two (irreversible part) extreme points that correspond to the equilibrium magnetization value(s). In Fig. 10a,b we compare the results of the SW model for the angular dependence of H_c and H_{eb} with the Monte Carlo data.

We find that the Monte Carlo simulation data for the angular dependence of H_{eb} and H_c can be satisfactorily described by a SW model with an effective off-axis unidirectional anisotropy making an angle $\phi_b \sim 5^\circ$ with the nanowire axis. As previously, reported in the case of FM/Af bilayers, an effective off-axis anisotropy arises from the frustration of the AF interface moments due to interface roughness [29]. In the case of core-shell nanowires studied here, the source of magnetic frustration is the anisotropy disorder occurring at the core-shell interface due to shell granularity.

As a final remark, we discuss briefly recent experiments on electrodeposited Co/CoO nanowires[21], which showed giant exchange bias and an effective off-axis unidirectional anisotropy at an angle $\phi_b \sim 30^\circ$ leading to an $\sim 20\%$ increase of the bias field when the cooling field is applied at $\phi_H \sim 30^\circ$ relative to the wire axis. Our simulations for Co/CoO nanowires, reproduce a similar behavior, namely the appearance of an off-axis effective anisotropy ($\phi_b \sim 5^\circ$) and a weak ($\sim 10\%$) increase of the bias field when the reversing field is applied at an angle $\phi_H \sim 1^\circ$ relative to the nanowire axis. Most importantly, our simulations point to the shell polycrystallinity as a source of generating effective off-axis anisotropy and optimum field directions for maximizing the EB effect in magnetic core-shell nanowires. However, the quantitative discrepancy between our simulations results and the experimental findings[21] we believe that is caused by the relative strong EB effect in these samples, which most probably stems from atomic scale details of the interface structure leading to strong uncompensation, as for example, crystallographic orientation, interface roughness, alloying, etc, which are not considered in the present model.

4. Summary

We have studied the isothermal magnetic hysteresis of cylindrical Co/CoO nanowires with core-shell morphology using a classical spin model and Monte Carlo simulations. We have demonstrated that polycrystallinity of the CoO shell causes enhancement of coercivity and suppression of exchange-bias field relative to the monocrystalline shell. This behavior is mainly attributed to enhanced drag of the AF interface spins during reversal of the core spins. The same mechanism is responsible for reduction of domain wall mobility. Additionally, Co/CoO nanowires with monocrystalline shell, exhibit a weak ($\approx 10\%$) increase of their bias field when the reversing field is applied at a small angle ($\approx 10^\circ$) relative to the nanowire axis. On the other hand, shell granularity introduces an effective off-axis ($\phi_b \sim 5^\circ$) unidirectional anisotropy due to frustration of the shell interface spins, leading to weak increase ($\sim 10\%$) of the bias field in an off-axis direction. Our results are in qualitative agreement with recent experimental observations in Co/CoO nanowires[21], and point to shell polycrystallinity as a source of generating off-axis unidirectional anisotropy

in FM core - AF shell nanowires and exchange bias enhancement in off-axis directions.

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