Magnetic ground and remanent states of synthetic metamagnets with perpendicular anisotropy

N. S. Kiselev¹, U. K. Rößler¹, A. N. Bogdanov¹ and O. Hellwig²

¹ IFW Dresden, Postfach 270116, D-01171 Dresden, Germany
² San Jose Research Center, Hitachi Global Storage Technologies, San Jose, CA 95135, USA
E-mail: m.kyselov@ifw-dresden.de

Abstract.

In this work, we summarize our theoretical results within a phenomenological micromagnetic approach for magnetic ground state and nonequilibrium states as topological magnetic defects in multilayers with strong perpendicular anisotropy and antiferromagnetic (AF) interlayer exchange coupling (IEC), e.g. [Co/Pt(Pd)]/Ru(Ir, NiO). We give detailed analysis of our model together with the most representative results which elucidate common features of such systems. We discuss phase diagrams of the magnetic ground state, and compare solutions of our model with experimental data. A model to assess the stability of so-called tiger tail patterns is presented. It is found that these modulated topological defect cannot be stabilized by an interplay between magnetostatic and IEC energies only. It is argued that tiger tail patterns arise as nuclei of ferro-stripe structure in AF domain walls and that they are stabilized by domain wall pinning.

1. Introduction

AF coupled superlattices with strong perpendicular anisotropy, as [Co/Pt(Pd)]/Ru (Ir) or [Co/Pt]/NiO [1–4], are considered as promising candidates for nonvolatile magnetic recording media, spin electronics devices, high-density storage technologies, and other applications [5]. Owing to the strong competition between antiferromagnetic interlayer exchange (IEC) and magnetostatic coupling these nanoscale superlattices are characterized by a large variety of multidomain states, unusual magnetization processes [1–3,8], and other specific effects [3,4,6,7] which have no counterpart in common layered systems with perpendicular magnetization [9]. Theoretical description of magnetic states and reversal magnetization process, however, can be achieved within the known phenomenological framework of micromagnetism and magnetic domain theory [9]. Here we give an overview of our model used to describe magnetic ground states in AF coupled multilayers.

2. The ground magnetic state

In ferromagnetic exchange decoupled or ferromagnetically coupled multilayers, e.g., pure Co/Pt or Co/Pd multilayers the magnetic ground state is a multidomain state [13]. For the theoretical description of this state a model of magnetic stripe domains is usually used. First this model has been formulated for a single ferromagnetic plate with perpendicular anisotropy by Kittel [10]. Later, it has been developed for ultra thin ferromagnetic single films by Malek and Kambersky [11] and independently by Kooy and Enz [12]. This model is based on a few assumptions: (i) The
Figure 1. (a) Schematic representation of regular stripe domains with period $D$ in a perpendicularly magnetized $\{\text{Co/Pt}_{X-1}/\text{Co/Ru}\}_N$ multilayer with $N = 4$, $X = 2$. AF coupling favors a lateral shift $\alpha$ of domain walls in adjacent [Co/Pt] stacks. The arrows show four pairs of interacting charged surfaces, for details see the text. (b) Magnetic phase diagram of the ground state for AF coupled bilayers in terms of reduced magnetic layer thickness $t/l_c$ and interlayer exchange $\delta/l_c$ ($\delta = J_{ex}/(2\pi M_s)$). Thick blue line indicates the first-order transitions between ferromagnetic state (shifted ferro-stripes (A)) and antiferromagnetic states (single domain state (B) and AF-stripe state (C)). At the vertical dashed line $t_{c1} = 2.08 l_c$, the AF-stripes continuously transform into the single domain state. These lines meet in a critical point $t = t_{c2}$, $\delta = \delta_{c2} = 0.639 l_c$, hollow circle. The stability region of the shifted ferro-stripes (A) is limited by the lability line (thin black). Shaded area correspond to the mixed state where FM stripe and AF states can coexist. The energy profiles corresponding to enumerated points (1)-(5) along the sections of the phase diagram at $t/l_c = 1$ and 3 are shown in Fig. 2 (a)-(b). (c) Magnetic phase diagram of the ground state of multilayers depending on number of magnetic layers in each ferromagnetic stack $X$ and number of stacks $N$. All notations are the same as in figure (b). Symbols correspond to experimental data for $\{\text{Co/Pt}_{X-1}/\text{Co/Ru}\}_N$, Ref. [3].

material is uniaxial with the direction of the magnetization normal to the surface of the plate. (ii) The plate has the uniform thickness $t$ and its lateral dimensions in the $x$ and $y$ directions are infinite. (iii) The anisotropy $K_u$ is strong ($Q = K_u/(2\pi M_s^2) \gg 1$), so that no closure domains occur. (iv) The domain structure consists of straight periodical domains with the period $D$ and the magnetization as well as the $180^\circ$ uncharged Bloch walls are perpendicular to the surface.

The stripe domain model has been extended for the case of multilayers with alternate ferromagnetic and nonmagnetic layers by Draaisma and de Jonge [13]. In these multilayers the dipolar coupling between magnetic layers can be considered as result of interactions between magnetostatic “charges” on the surface of each magnetic layer. As a result, the magnetization of the layers are strictly parallel across the multilayer and their direction alternates laterally in a ferro-stripe configuration. In this model it is assumed that the domain walls in the layers sit exactly on top of each other [13]. For the case of exchange decoupled and ferromagnetically coupled multilayers this assumption is reasonable because there are no intrinsic forces which favor a distortion of the domain wall configuration. However, for the case of AF IEC which favors antiparallel alignment of magnetic moments at the Co-Ru-Co interfaces this assumption becomes invalid in general. In Ref. [14] we have introduced a model for the magnetic ground state in such multilayers. It considers that AF coupling causes a lateral shift of the domain
walls in the adjacent ferromagnetic stacks. As is seen from Fig. 1 (a), within the region of the lateral shift the magnetic moments at Co-Ru-Co interfaces are ordered antiparallel. This gives an energy gain due to AF coupling. The energy contribution from IEC is then proportional to the width of this area \( a \). Exchange energy density per one magnetic layer is then:

\[
e_{\text{ex}} = \frac{(N-1)J_{\text{ex}}}{2\pi M_s^2} \left(1 - \frac{|a|}{D}\right)
\]

where \( J_{\text{ex}} \) is the interlayer exchange constant. The magnetostatic energy density per magnetic layer of ferro-stripe domains with lateral shift is:

\[
e_d = \frac{4D}{\pi^2} \sum_{n=0}^{\infty} \left[f_n(t) + \sum_{k=1}^{N-1} \sum_{j=k+1}^{NX} \left\{ \cos \left(\frac{2\pi na}{D} \Gamma_{kj}\right) f_n(L_{kj} + t) + f_n(L_{kj} - t) - 2f_n(L_{kj}) \right\} \right],
\]

with

\[
f_n(t) = \left[1 - \exp(-2\pi ntD)\right] n^{-3},
\]

\[
L_{kj} = \sum_{i=k}^{j-1} [t + s_i],
\]

\[
s_i = \begin{cases} s_{\text{Ru}}, & i = mX, m = 1, \ldots, N, \text{ and } \\ s_{\text{Pt}}, & \text{otherwise,} \end{cases}
\]

\[
\Gamma_{kj} = \begin{cases} 1, & 2mX + 1 \leq k \leq (2m + 1)X, (2m + 1)X + 1 \leq j \leq (2m + 2)X, m = 0, 1, 2, 3, \ldots, \\ 0, & \text{otherwise.} \end{cases}
\]

In Eq. (2) the summation is over all pairs of magnetic layers. The expression under the double summation sign is the magnetostatic interaction energy between two Co layers separated by distance \( L_{kj} \) between the centers of the layers. It equals the sum of interactions between the four charged surfaces of the layers pairs. Figure 1 (a), illustrates one such pair. Four double-ended arrows correspond to four coupled surfaces. As AF coupling is provided by Co-Ru-Co interfaces, the lateral shift equals zero for the pairs of layers which belong to the same stack or for two layers belonging to different stacks, if they have both even or odd number in the multilayer (see Fig. 1 a). This assumption is reflected by the factor \( \Gamma_{kj} \). Thereby, the total energy density per surface unit of the AF coupled multilayer is

\[
e_{\text{tot}} = e_{\text{ex}} + e_d + NX4\lambda_c t/D,
\]

where \( e_{\text{ex}} \) and \( e_d \) are defined by Eqs. (1) and (2), respectively, \( \lambda_c = \gamma_w/(4\pi M_s^2) \) is the characteristic length, \( \gamma_w \) is the domain wall energy density.

The simplest case of a multilayer with \( N = 2 \) and \( X = 1 \) is representative for multilayers with arbitrary \( X \) and even \( N \) \([14,16,17]\). The results of minimization of the total energy with respect to both parameters \( a \) and \( D \) are reflected in the phase diagram Fig. 1 (b), and in Figs. 2. The main features of the solutions are the following: (i) Ferro-stripes are the ground state of an FM coupled \( J_{\text{ex}} < 0 \) and exchange decoupled \( J_{\text{ex}} = 0 \) multilayer up to \( t \to 0 \), see Fig. 1 (b). (ii) For \( J_{\text{ex}} > 0 \) \( (\delta/\lambda_c > 0, \text{AF coupling}) \) a ferro-stripe state with a small shift remains the ground state up to some critical value of \( \delta \) and then transforms to the state with AF arrangement by a first order transition marked by thick blue line in Fig. 1 (b), compare energy profiles (2) in Fig. 2. (iii) In wide range of the thickness \( t \) and exchange \( \delta \) ferro-stripes can exist as metastable states. Here, solutions for the ferro-stripes correspond to local energy minima of the system that are separated by a barrier from the global minimum corresponding to the homogeneous \( (D \to \infty) \) AF state (see energy profiles (3) in Fig. 2). (iv) At the lability line (thin black line in Fig. 1 (b)) the barrier vanishes and the solution for the ferro-stripe state becomes unstable with respect to the lateral shift \( a \), curves (4) and (5) in Fig. 2. (v) For thick ferromagnetic layers \( t \) above the transition line the ground state of the system is a stripe configuration with antiparallel arrangement, see inset (C) in Fig. 1 (b). These \textit{AF-stripes are always} stable with respect to
a lateral shift, see potential well for \( a = D/2 \) in Fig. 2 (b). On the contrary, the solutions for the ferro-stripe phase has a finite shift, see inset (A) in Fig. 1 (b), and Figs. 2 (a), (b). These results are supported by the analytical calculation and simple physical arguments [14].

(vi) With decreasing magnetic layer thickness \( t \) the period of AF-stripes increases and at some critical thickness, see dashed vertical line in Fig. 1 (b), AF-stripes continuously transform into the AF homogeneous state \( (D_{AF}(t_{cr}) \to \infty) \). Thus, AF-stripes form equilibrium phases only for thicker layers, \( t > t_{cr} \), and for sufficiently strong AF coupling \( \delta > \delta_{cr} \).

In Fig. 1 (c) the ground state phase diagram for \([Co/Pt]\times_{1}/Co/Ru\) multilayers depending on number of Co layer per each stack \( X \) and number of stacks \( N \) is shown together with experimental data for a corresponding multilayer system studied in Refs. [2, 3]. The ground state of the system small \( X \) on the left of the lability line (black thin line) is the homogeneous AF state. For large \( X \) on the right of the transition line (blue thick line) the ferro-stripes are the ground state. Theoretically calculated lability and transition lines define the region for a mixed state, where metastable ferro-stripes and homogeneous AF state can coexist (shaded area). This phase diagram results from direct minimization of Eq. (3) with respect to both free parameters \( a \) and \( D \) for the fixed material parameters indicated in the figure. We have estimated the value of \( t_{cr} = 4.43 \) nm, as a best fit of the experimentally measured dependence of stripe domain period versus number of cobalt layers \( X \) in a pure \([Co/Pt]\times\) multilayer [3,15]. For \( \delta = 0.363 \) nm which fits well experimental data, and \( M_{s} = 1420 \) emu/cm\(^3\), typical value for a bulk cobalt, we estimated \( J_{ex}=0.46 \) erg/cm\(^2\) which is in a good agreement with 0.45 erg/cm\(^2\) found in the experiment [3]. Therefore, for \([Co/Pt]/Ru\) multilayers \( \delta/t_{c} = 0.08 \) which is about one order of magnitude smaller than the critical value \( \delta_{cr}/t_{c} = 0.639 \), see phase diagram Fig. 1 (b). For \([Co/Pt]_{3}/NiO/[Co/Pt]_{3}\) with the largest values of \( J_{ex} = 0.044 \) erg/cm\(^2\) [7] the value of \( \delta \) is even about one order of magnitude smaller than in \([Co/Pt]/Ru\) systems. Thus, in \([Co/Pt]/Ru\) and \([Co/Pt]/NiO\) multilayer systems the ground state of the system is either ferro-stripe state or homogeneous AF state, area (A) and (B) respectively in Figs. 1 (b) and (c). This is in agreement with the experimental observations [2, 3].

Figure 2. (a) and (b) are the energy profiles with respect to reduced parameter \( 2a/D \) measured from the AF state \( (a = D/2) \). The numbers of the profiles correspond to the points along the sections of the phase diagram shown in Fig. 1 (b) for the fixed values \( t/l_{c} = 1 \) (a) and 3 (b). For each point of the profiles we find an equilibrium value of \( D \) defined by the condition \( \partial e_{tot}/\partial D = 0, \partial^{2} e_{tot}/\partial D^{2} > 0 \). Stable or metastable shifted ferro-stripes correspond to the potential wells marked by hollow circles in the energy profiles (1)-(5). Solid circles correspond to the potential well for the AF single domain state \( (D \to \infty) \) in (a), and the unshifted AF stripes in (b). Figure (c) illustrates a strong variation of the equilibrium value of \( D \) with respect to the lateral shift \( a \) at the transition line between FM and AF which correspond to the energy profiles marked by (2) in figures (a) and (b).
3. The mystery of “tiger tails”

In Refs. [17,18] we have shown that within homogeneous AF state different types of topological defects can appear. The main types of these defects include ferrobands, sharp domain wall, and metamagnetic band. The last one is formed in the system during magnetization reversal processes and essentially is the trapped metamagnetic domain which can exist as a metastable state even at zero field, for details see Refs. [17–19]. The isolated sharp domain wall and the ferroband exist in remanent states as planar defects separating antiferromagnetically arranged regions. The ferroband, Fig. 3 (a), with finite width \( w \) and sharp domain wall \( (w = 0) \) are separated by a finite energy barrier. The ferroband arises in AF coupled multilayers due to the interplay between magnetodipole and interlayer exchange interactions [17,18].

There is a lot of evidence for an instability of ferromagnetic band defects into a modulated “tiger tail” pattern, which is a periodical multidomain state with ferromagnetic arrangement through the whole multilayer, see inset in Fig. 3 (c). To investigate the stability of the homogeneous ferroband with respect to a transformation into tiger tail patterns we consider the model schematically shown in Fig. 3 (b), for \( N = 2, X = 1 \). Magnetization distribution in each ferromagnetic layer is considered as two semi-infinite plates with opposite magnetization, separated by the bar-shape region of width \( w \), and infinite length in \( y \)-direction. We assume that these bars are composed of regular up-down domains with period \( D_{tt} \) and infinitely thin domain walls perpendicular to the edges of the bar. The total energy of the tiger tail patterns \( e_{tt} \) then consists of dipolar interaction energy between semi-infinite planes, self magnetostatic energy of two bars split into domains, dipolar interactions between these bars, interlayer exchange coupling energy which is proportional to \( w_{tt} \) and domain wall energy along bent profiles as shown in the inset in Fig. 3 (c). Magnetostatic energy interactions in this problem can be expressed in term of magnetic charges and functions \( G_{20} \) and \( F_{200} \) introduced by Hubert and Schäfer for infinite band-shaped and rectangular-shaped elements, respectively [9]. Note, because of the symmetry of the problem, the interaction energy between bars and semi-infinite plates equals zero. Minimization of the total energy of the tiger tail \( e_{tt} \) with respect to period of domains \( D_{tt} \) and width of band \( w_{tt} \) gives the solutions for equilibrium states. The rigorous mathematical treatment of this problem will be reported elsewhere [20]. Here, we highlight only as a representative result a solution for \( N = 2, X = 1 \) and corresponding material and geometrical parameters in zero magnetic field, Fig. 3 (c). The main features of the solution for the tiger tail model are as follows: (i) For \( 0 < t < t_b \) the global minimum of the system is a sharp domain wall \( (w_{tt} \equiv 0) \) which theoretically exists up to \( t \to \infty \). For \( 0 < t < t_a \) a sharp domain wall is the sole solution of the system. (ii) For \( t_a < t < t_c \) there are stable solutions for a homogeneous ferroband with both finite \( w_{tt} \) and \( D_{tt} \) up to the transition line (vertical blue line in Fig. 3 (c)) ferrobands correspond to the global minimum of the system. (iii) Above \( t > t_c \) the global minimum of the system corresponds to the regular ferro-stripe state with finite \( D_{tt} = D_{PS} \) and \( w_{tt} \to \infty \). In Refs. [17,18] we derived analytical equations for the lower limit for ferroband existence \( t_a \). In the interval \( t_b < t < t_{tr} \) up to the transition line (vertical blue line in Fig. 3 (c)) ferrobands correspond to the global minimum of the system. (iv) At \( t = t_c \) the energy barrier between metastable ferroband (doted line) and ferro-stripe state disappears. \( t_c \) is the upper limit for the ferroband existence. For \( t > t_c \) the global minimum of the system is strictly speaking the shifted ferro-stripe, see Sec. 1. (v) A equilibrium solutions for the tiger tail pattern with finite \( w_{tt} \) and \( D_{tt} \) (inset in Fig. 3 (c)) which satisfy the conditions for a global or a local energy minimum of the system do not exist. (vi) However, on the assumption that width of the defect band \( w_{tt} \) is a fixed geometrical parameter, and \( D_{tt} \) is the only free parameter of the system, the solutions for tiger tail pattern with finite \( D_{tt} do exist \) in a wide range of thickness \( t \), dashed area in Fig. 3 (c).

Tiger tail patterns, therefore, appear in the region of the phase diagram where the homogeneous AF state becomes instable towards the ferro-stripe state. Along a topological ferroband defect an instability can create a modulated domain configuration, which can be achieved by a local meandering of the domain walls in the magnetic layer, while a widening
of the band is prevented by domain wall pinning. This suggests that tiger tail patterns are modes of an inhomogeneous nucleation of ferro-stripes in 1-dimensional topological defects of the antiferromagnetic state. In AF multilayer systems, as \{[Co/Pt]_{X-1}/Co/Ru\}_N, topological defects with freely mobile or with pinned domain walls have been observed simultaneously [3]. Likely, crystalline grain boundaries act as pinning centers in these materials [3].

In conclusion, we have demonstrated that, according to our theoretical model and experimental observation, the ground state of AF coupled multilayers is either AF homogeneous or a ferromagnetic multidomain state, see Fig. 1 (c). Within the AF state there are different topological defects. Contrary to sharp domain walls and ferrobands, the tiger tail pattern cannot be stabilized by an interplay between magnetostatic and IEC energies only, but it can be stabilized by domain wall pinning.

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