Magnetic properties of layered nanorings

J. Escrig, P. Landeros, and D. Altbir[a)]
Departamento de Física, Universidad de Santiago de Chile (USACH), Av. Ecuador, 3493 Santiago, Chile

M. Bahiana and J. d'Albuquerque e Castro
Instituto de Física, Universidade Federal do Rio de Janeiro, CP 68528, 21941-972 Rio de Janeiro, Brazil

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The magnetic structure of nanorings consisting of alternate layers of magnetic and nonmagnetic materials is investigated as a function of their geometry. Phase diagrams giving the relative stability of characteristic internal magnetic configurations of the rings are obtained. Attention is focused on the condition for occurrence of the vortex configurations, in which case the layered structure might be used to produce magnetoresistive random access memories. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2356692]

Patterned arrays of compositionally modulated nanoparticles have received a great deal of attention in recent years. One of the reasons is the fact that these structures provide the basic magnetic architecture required to produce magnetoresistive random access memory (MRAM) devices.[1–3] Indeed, the fabrication of dense and fast MRAMs has become an important issue in the field of magnetism. As a consequence, the magnetic properties of layered magnetic nanoparticles have been intensively investigated.[2,4,5] In particular, interest has been focused on layered nanoring structures, on the basis of which a high density MRAM design was proposed six years ago by Zhu *et al.*,[2] taking advantage of the possible existence in magnetic nanorings of vortex states.[6,7]

Rothman *et al.*[8] have found that single-layer nanorings may also exhibit bidomain states, which they called onion state, characterized by two head-on (180°) walls at opposite ends of a diameter. The occurrence of such a state depends on the ring geometry. In a recent study of the internal magnetic configuration of nanorings, Landeros *et al.*[9] have shown that the onion states can be well described by a simple analytical model depending on a variational parameter n determined so as to minimize the ring total energy. In their model, $n=1$ corresponds to an in-plane ferromagnetic configuration. They found that when the onion configuration is the stable one n turns out to be very close to 1. This is in agreement with the work of Beleggia *et al.*,[10] who argued that as far as the magnetic phase diagram of single nanorings is concerned, replacing the more correct quasiuniform states with simple ideal uniform states should lead to errors in the position of the phase boundaries not exceeding 10%. In the present work we take these points under consideration and approximate the onion state by an idealized uniform configuration corresponding to $n=1$. In addition to the vortex and the onion configurations, nanorings may exhibit an out-of-plane ferromagnetic state.[9–11]

The purpose of this letter is to investigate the conditions under which individual magnetic rings in a layered structure exhibit one of three possible configurations, namely, out-of-plane ferromagnetic ($c=1$), "idealized onion" ($c=2$), and vortex ($c=3$). We consider structures consisting of two magnetic rings separated by a nonmagnetic one, as depicted in Fig. 1. Their geometry is characterized by the external R and internal a radii, the heights H_1 and H_2 of the lower and upper magnetic layers, respectively, and the thickness d of the nonmagnetic layer. We focus on the relative stability of the magnetic configurations of the layered ring, which can be identified by two indices $[c_1,c_2]$, where $c_1,c_2=1$, 2, or 3 correspond to the internal configurations of the lower and upper magnetic rings, respectively.

We adopt a simplified description of the system, in which the discrete distribution of magnetic moments is replaced with a continuous one characterized by a slowly varying magnetization $\mathbf{M}(\mathbf{r})$. The total energy $E_{\text{tot}}^{[c_1,c_2]}$ is generally given by the sum of three terms corresponding to the magnetostatic ($E_{\text{dip}}^{[c_1,c_2]}$), the exchange ($E_{\text{ex}}^{[c_1,c_2]}$), and the anisotropy ($E_K^{[c_1,c_2]}$) contributions. Here we are interested in soft or polycrystalline magnetic materials, in which case $E_K^{[c_1,c_2]}$ can be safely neglected.

The total magnetization can be written as $\mathbf{M}(\mathbf{r})=\mathbf{M}_1(\mathbf{r})+\mathbf{M}_2(\mathbf{r})$, where $\mathbf{M}_1(\mathbf{r})$ and $\mathbf{M}_2(\mathbf{r})$ are the magnetization of the lower and upper nanorings, respectively. In this case, the magnetostatic potential $U(\mathbf{r})$ splits up into two components, $U_1(\mathbf{r})$ and $U_2(\mathbf{r})$, associated with the magnetization of each individual nanoring. Then, the total dipolar energy can be written as $E_{\text{dip}}^{[c_1,c_2]}=E_d(c_1,c_1)+E_d(c_2,c_2)+2E_d(c_1,c_2)$, where $E_d(c_i,c_j)=(\mu_0/2)\int \mathbf{M}_i(\mathbf{r})\nabla U_j(\mathbf{r})dv$, with $i,j=1,2$. The diagonal terms, $E_d(c_i,c_i)$, are the dipolar contributions to the self-energy of the individual magnetic nanorings, whereas the off-diagonal one, $E_d(c_1,c_2)$, is the dipolar interaction between them.

The exchange energy $E_{\text{ex}}^{[c_1,c_2]}$ has also three contributions, two coming from the direct exchange interaction within the magnetic rings and the other one from the indirect interaction between them mediated by the nonmagnetic ring. Since the indirect interaction decays rapidly with the thickness of the nonmagnetic ring, it can be neglected provided d is suffi-

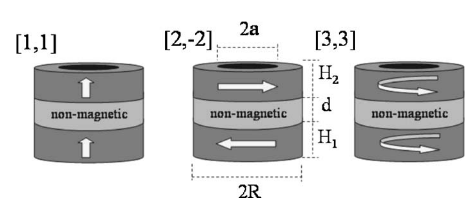

FIG. 1. Magnetic configurations of layered nanoring.

[a)]Electronic mail: daltbir@lauca.usach.cl ciently large. A good estimate of the range of the indirect exchange interaction can be obtained from the results for multilayers.[12] As a general result, the interlayer exchange coupling vanishes for spacer thicknesses greater than a few nanometers, which does not exceed the value of the exchange length l_{ex} of ferromagnetic metals. Here we focus our attention on those cases in which d is not smaller than the magnetic material's l_{ex}, thus to a good approximation $E_{ex}^{[c_1,c_2]}$ can be written as $E_x(c_1)+E_x(c_2)$, where $E_x(c_i)=A\int[(\nabla m_{ix})^2+(\nabla m_{iy})^2+(\nabla m_{iz})^2]dv$.[13] Here, $\mathbf{m}_i=(m_{ix},m_{iy},m_{iz})=\mathbf{M}_i/M_0$ is the magnetization normalized to the saturation magnetization M_0 and A is the stiffness constant of the magnetic material. In the expression for $E_x(c_i)$, a constant and configuration independent term, equal to the exchange energy in the ferromagnetic state, has been left out.[13]

On the basis of the above results, the total energy of the layered structure can be written in the form $E_{tot}^{[c_1,c_2]}=E_{self}^{[c_1]}(1)+E_{self}^{[c_2]}(2)+E_{int}^{[c_1,c_2]}$, where $E_{self}^{[c_i]}(i)=E_d(c_i,c_i)+E_x(c_i)$ is the self-energy of each magnetic nanoring $(i=1,2)$ and $E_{int}^{[c_1,c_2]}=2E_d(c_1,c_2)$ is the (dipolar) interaction energy between them. We now proceed to the calculation of the energy terms in the expression for $E_{tot}^{[c_1,c_2]}$. Results will be given in units of $\mu_0 M_0^2 l_{ex}^3$, i.e., $\widetilde{E}=E/\mu_0 M_0^2 l_{ex}^3$, where $l_{ex}=\sqrt{2A/\mu_0 M_0^2}$.

In order to perform the integrals in the expressions above, it is necessary to specify the functional form of the magnetization for each configuration. For $c=1$, $\mathbf{M}_i(\mathbf{r})$ can be approximated by $M_0\hat{z}$, where $\hat{z}$ is the unit vector parallel to the axis of the nanoring, whereas for $c=2$, $\mathbf{M}_i(\mathbf{r})$ can be taken equal to $M_0\hat{x}$, where $\hat{x}$ is a unit vector parallel to the basis of the nanoring. In these two cases, we find that the reduced self-energies take the form

$$\widetilde{E}_{self}^{[c]}(i)=\frac{\pi R^3}{l_{ex}^3}\int_0^\infty \frac{dq}{q^2}F(c,i)(J_1(q)-\beta J_1(\beta q))^2,$$

where $F(1,i)=(1-e^{-q\gamma_i})$ and $F(2,i)=(e^{-q\gamma_i}+q\gamma_i-1)/2$. Here, $\beta=a/R$, $\gamma_i=H_i/R$, and $J_1(z)$ is a Bessel function of the first kind. In both cases, the exchange contribution to the self-energies vanishes. Finally, in configuration $c=3$, $\mathbf{M}_i(\mathbf{r})$ can be approximate by $M_0\hat{\phi}$, where $\hat{\phi}$ is the azimuthal unit vector. In such case the contribution from the dipolar energy to the self-energy results equal to zero, and $\widetilde{E}_{self}^{[3]}(i)=E_x(3)=-(\pi H_i \ln\beta)/l_{ex}$.

Regarding the interaction between the magnetic rings, the only nonzero terms correspond to those cases in which both rings are in the same configuration, either $c=1$ or $c=2$. Due to the condition of perfect flux closure in the vortex configuration, one magnetic ring in such configuration does not interact with the other, independently of the magnetic configuration of the latter. In addition, it is easy to show that the interaction energies in the [1, 2] and [2, 1] configurations are zero. Thus, we end up with just

$$\widetilde{E}_{int}^{[1,1]}=-\frac{\pi R^3}{l_{ex}^3}\int_0^\infty \frac{dq}{q^2}G(1,2)(J_1(q)-\beta J_1(q\beta))^2,$$

where $G(1,2)=e^{-q(d/R)}(1-e^{-q\gamma_1})(1-e^{-q\gamma_2})$ and $\widetilde{E}_{int}^{[2,-2]}=\widetilde{E}_{int}^{[1,1]}/2$. The minus sign in the superscript of $\widetilde{E}_{int}^{[2,-2]}$ indicates that the alignment of the magnetizations of the lower and upper rings is antiparallel. We remark that the total energy of the [2, 2] configuration is always larger than that of the [2,−2] one.

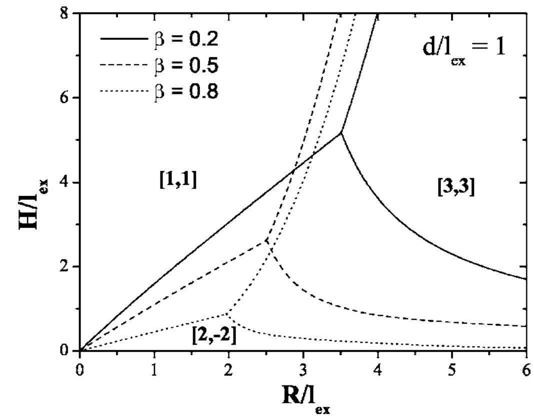

FIG. 2. Phase diagrams for layered nanoring with $H_1=H_2=H$ for $\beta=a/R=0.2$, 0.5, and 0.8.

We are in position to investigate the relative stability of the various $[c_1,c_2]$ configurations. We consider first systems with $H_1=H_2=H$. Figure 2 shows the phase diagrams giving the regions in the RH plane within which one of the $[c_1,c_2]$ configurations is of lowest energy, for $d=l_{ex}$, and $\beta=0.2$ (solid lines), 0.5 (dashed lines), and 0.8 (dotted lines). The diagrams show three regions, corresponding to configurations [1, 1], [2,−2], and [3, 3], as in the case of a single nanoring.[9] It is worth mentioning that in our model the [3, −3] configuration, corresponding to a vortex and an antivortex, and the [3, 3] one have the same energy, since in both cases the magnetic nanorings do not interact. In which follows we shall refer to both as [3, 3] configurations.

Similar to the case of a single nanoring, the phase diagram changes with β. The dependence of the whole diagram on the value of d can be investigated by looking at the trajectories of the triple point in the RH plane as functions of β. Such trajectories are shown in Fig. 3 for different values of the ratio d/l_{ex}. We remark that the radius R_t of the triple point represents the smallest value of R for which the [3, 3] configurations are stable. We clearly see that the trajectories rapidly approach a limiting one (dashed line) corresponding to completely uncoupled rings $(d \gg l_{ex})$. In such case, the phase diagram is reduced to that for single magnetic nanorings.[9]

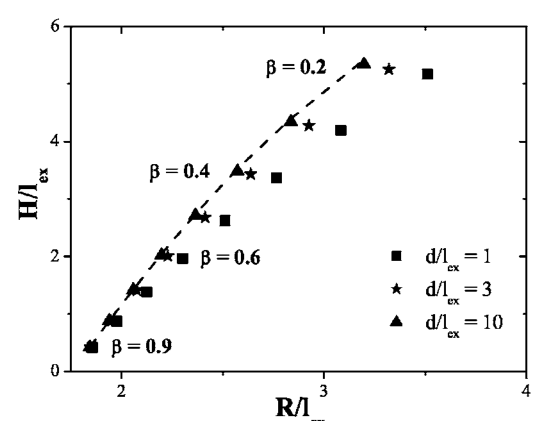

FIG. 3. Trajectories of the triple point in the phase diagrams in Fig. 2 as functions of β, for $d/l_{ex}=1$ (squares), 3 (stars), and 10 (triangles). The dashed line corresponds to the case in which the magnetic rings are completely uncoupled $(d \gg l_{ex})$.

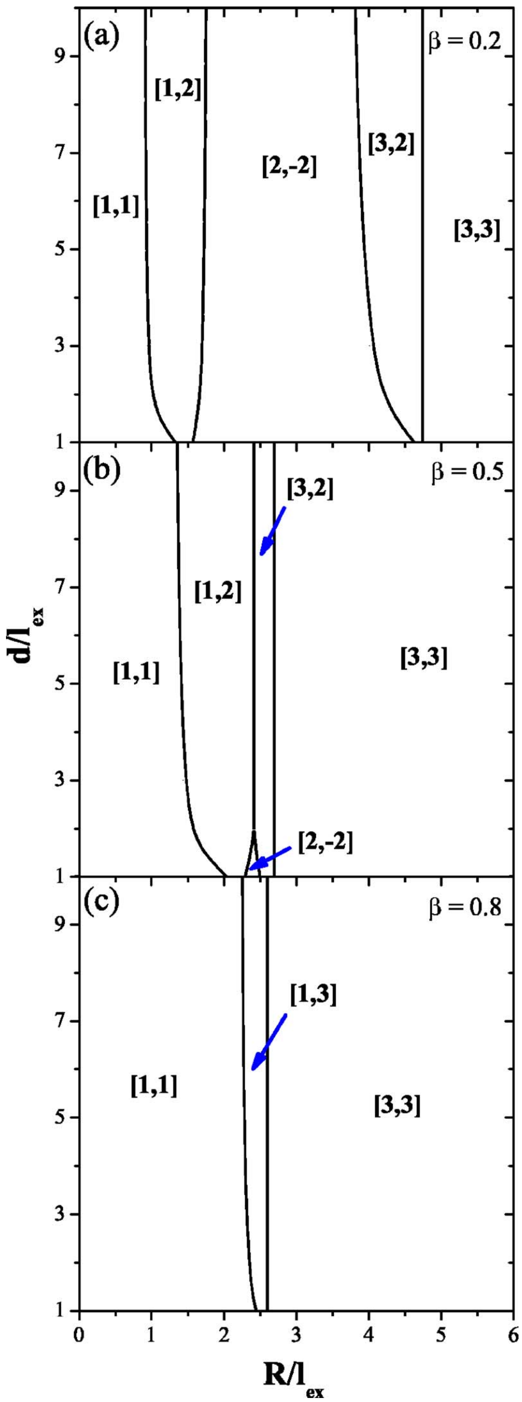

FIG. 4. (Color online) Phase diagrams for layered nanoring with $H_1=3l_{ex}$ and $H_2=H_1/2$ in the Rd plane, for $\beta=0.2$ (a), $\beta=0.5$ (b), and $\beta=0.8$ (c).

We now turn our attention to the case in which H_1 and H_2 are different. Figure 4 shows the diagrams corresponding to $H_1=3l_{ex}$ and $H_2=H_1/2$, for $\beta=0.2$ (a), 0.5 (b), and 0.8 (c). We immediately see that the occurrence of the [3, 3] configurations is to an excellent approximation independent of the thickness d of the nonmagnetic ring, provided $d \geq l_{ex}$. In addition, the minimum value of R for which such configurations occur may be as small as a few l_{ex}, provided β is not too small.

In conclusion, we have studied the magnetic behavior of nanorings composed of alternate layers of magnetic and nonmagnetic materials. In particular, we have investigated the size range of the geometric parameters for which the vortex configurations [3, 3] are of lowest energy. Our results are summarized in phase diagrams which are intended to provide guidelines for the production of nanostructures with technological purpose such as the fabrication of MRAMs.

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