Surface anisotropy and surface spin canting in the semi-infinite ferromagnet

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In a semi-infinite ferromagnet with surface anisotropy, the spins near the surface may cant if the easy axis associated with the surface is noncollinear with the bulk magnetization. We show that such canting occurs only when the surface-anisotropy field H_s exceeds a critical value $H_s^{(c)}$, which is large compared to surface-anisotropy fields inferred from recent experiments.

Recent experiments have established[1-3] that in ultrathin ferromagnetic films, the ground-state spin orientation is influenced crucially by very strong-anisotropy fields which act on spins in the surface, or at an interface. This has the consequence that films with thickness in the range of one or a very few monolayers will have their magnetization oriented normal to the surfaces, if the easy axes of the anisotropies present are also normal to the surface, as encountered frequently.

Recently, ferromagnetic resonance and Brillouin scattering has been employed to infer the nature of the surface anisotropy present on a thick Fe crystal with a (100) surface.[1] The surface-anisotropy field found in this work has strength comparable to values inferred for the ultrathin films, and again the easy axis is normal to the surface. The external magnetic field present in these experiments was parallel to the surface; in the analysis of their data, these authors assume the static magnetization of the sample is spatially uniform and everywhere parallel to the surface.

With the external field present parallel to the surface, and strong surface anisotropy with easy axis normal to it, the magnetization in the bulk of the crystal is surely parallel to the surface but one may expect spin canting near the surface. If such canting occurs, the anisotropy constant inferred from the data of Ref. 3 should be viewed as an effective anisotropy constant, related to the actual anisotropy experienced by surface spins by an analysis which takes explicit account of the presence of spin canting and its influence on the spin waves excited in the resonance experiment.

The purpose of this Brief Report is to present a simple calculation which explores the conditions that must be met for such spin canting to occur. We find that the effective surface-anisotropy field H_s must exceed a critical value $H_s^{(c)}$ for surface spin canting to occur. When $H_s < H_s^{(c)}$, the spins are everywhere parallel to the surface, including within the surface layer itself. It is the case that $H_s^{(c)}$ is large compared to the values inferred from the data in Ref. 3. This result allows one to set aside the concern expressed in the previous paragraph.

We consider a semi-infinite ferromagnet, consisting of sheets of spins S labeled by the index l, with $l=0$ the surface sheet. The z axis is normal to the surface, and the spins in plane l are canted, to make an angle θ_l with respect to the xy plane, which is parallel to the surfaces. In the presence of the canting, the spin array generates a spatially varying demagnetizing field $h_z(l)$. The total energy of the system is written, in appropriate units,

$$E=-I\sum_{l=0}^{\infty}\mathbf{S}(l)\cdot\mathbf{S}(l+1)-\tfrac{1}{2}\sum_{l=0}^{\infty}h_z(l)S_z(l)-\frac{1}{2S}H_sS_z^2(0)\,, \tag{1}$$

where I is an effective interplanar exchange constant, and H_s is the surface-anisotropy field. [If the anisotropy energy per surface spin is written $K_sS_z^2(0)$, the effective magnetic field which enters the equations of motion of spin-wave theory is $2K_sS\equiv H_s$.] Also, we ignore the influence of the external magnetic field, whose influence will be to suppress surface spin canting.

We shall assume the canting angle θ_l varies slowly with l, so we may use a continuum approximation, a procedure valid for the transition-metal ferromagnets. Then, $h_z(l)$ may be found from the condition $\nabla\cdot\mathbf{B}=0$, which in our notation reads

$$\frac{\partial h_z}{\partial l}+4\pi n\mu\frac{\partial S_c}{\partial l}=0\,, \tag{2}$$

where n is the number of spins per unit volume and μ is the magnetic moment per spin. Since both S_z and h_z vanish as $l\rightarrow\infty$, where the magnetization is parallel to the surface, Eq. (2) is integrated to give

$$h_z(l)=-4\pi n\mu S_z(l)\,. \tag{3}$$

Then Eq. (1) becomes, with $M=4\pi n\mu$ the saturation magnetization,

$$E=IS^2\sum_{l=0}^{\infty}\cos(\theta_l-\theta_{l+1})+2\pi MS\sin^2(\theta_l)-\tfrac{1}{2}SH_s\sin^2(\theta_0)\,. \tag{4}$$

Upon minimizing the energy with respect to θ_l, one finds for $l\geq 1$

$$IS[\sin(\theta_l-\theta_{l+1})+\sin(\theta_l-\theta_{l-1})]+2\pi M\sin(2\theta_l)=0\,, \tag{5a}$$

and for $l=0$,

$$IS\sin(\theta_0-\theta_1)+2\pi M\sin(2\theta_0)-\tfrac{1}{2}H_s\sin(2\theta_0)=0\,. \tag{5b}$$

In the continuum limit, Eq. (5a) is replaced by

$$\frac{\partial^2\theta_l}{\partial l^2}-\frac{1}{2\xi^2}\sin(2\theta_l)=0\,, \qquad (6)$$

where $\xi=(D/4\pi M)^{1/2}$ and $D=IS^2$ is the spin-wave exchange stiffness constant. In this limit Eq. (5b) becomes a boundary condition:

$$D\left(\frac{\partial\theta}{\partial l}\right)_0+\tfrac{1}{2}(H_s-4\pi M)\sin(2\theta_0)=0\,. \qquad (7)$$

It is straightforward to integrate Eq. (6)

$$\tan(\tfrac{1}{2}\theta_l)=\tan(\tfrac{1}{2}\theta_0)\exp(-l/\xi)\,, \qquad (8)$$

and the boundary condition gives an expression for θ_0:

$$\cos(\theta_0)=\frac{4\pi M\xi}{H_s-4\pi M}\,. \qquad (9)$$

Values for surface and interface anisotropies inferred from experiments on ultrathin films, and also in the analysis of Ref. 3 for the single crystal of Fe, tend to lie in the range of 2 or 3 times $4\pi M_s$. One may infer this by noting that when the easy axis for the surface anisotropy is normal to the surface, the magnetization M of the monolayer is normal to it also. But by the time one reaches a few monolayers, the magnetization rotates to become parallel to the surface, by virtue of the energetically unfavorable demagnetizing fields generated when M is normal to the surface. The parameter ξ is the thickness of a Néel wall in the bulk material, calculated with bulk anisotropy ignored. The thickness of a Néel wall is several tens of layers in Fe ($\xi\sim 30$ Å).

The right-hand side of Eq. (9) is thus large compared to unity, and there is no solution for θ_0. Equation (6) and the boundary condition in Eq. (7) are satisfied identically by choosing $\theta_l\equiv 0$ everywhere, i.e., the magnetization is everywhere strictly parallel to the surface, as assumed in the analysis of Ref. 3. One has no surface spin canting when $H_s<H_s^{(c)}$, where

$$H_s^{(c)}=4\pi M(\xi+1)\,. \qquad (10)$$

When $H_s>H_s^{(c)}$, canting occurs and the energy of the spin system is lowered below that of the spatially uniform state by the amount

$$\Delta E=-2S\sin^2(\tfrac{1}{2}\theta_0)\times[H_s\sin^2(\tfrac{1}{2}\theta_0)+4\pi M\cos\theta_0]\,. \qquad (11)$$

The question of the spin arrangement in the limit of a small number of monolayers remains open and interesting. Studies of these cases are underway.

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