# Exotic Structures On Magnetic Multilayers

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**Abstract**

To characterize the possible magnetic structures created on magnetic multilayers a model has been formulated and studied. The interlayer inhomogeneous structures found indicate either (i) a regular periodic, (ii) a quasiperiodic change in the magnetization or (iii) spatially chaotic glass states. The magnetic structures created depend mainly on the ratio of the magnetic anisotropy constant to the exchange constant. With the increase of this ratio the periodic structures first transform into the quasiperiodic and then into the chaotic glass states. The same tendency arises with the depolarization of the magnetic moments of the first layer deposited on the substrate.

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Modern growth techniques, such as molecular beam epitaxy (MBE) or laser ablation, allow magnetic mono- or multilayers to be built up. The magnetic layers produced from $Fe$, $Ni$ or $Co$ may be separated by non-magnetic layers, produced, for example, from $Cu$. In these structures the magnetic films are grown one layer at a time. In many cases the single layer appears as a single domain, i.e. all magnetic moments having a single orientation [1]. When a second layer is grown on top of the first layer the orientation of magnetic moments in the second layer is not necessarily the same as in the first layer. Following addition of a third layer, the magnetic moments of this layer may have yet another orientation. The orientation of the magnetic moments is usually dictated by a competition between non-uniformity of exchange energy and anisotropy energy. Therefore, the questions arise : what kind of magnetic structures (analogous to the Bloch domain wall in bulk magnetic samples) may be created by the interaction between the monolayers in the film; how many types of structures can be created; what are the energy costs to create such a structure? The estimation of such energies and their hierarchy will indicate the possible temperatures and other conditions of the substrate needed for the creation of such structures.

To describe the magnetic structure in a (uniaxially symmetric) magnetic multilayer the exchange energy and the anisotropy energy have been taken into consideration. The exchange energy, $E_{ex}$, favours the alignment of the magnetic moments of atoms and the magnetic anisotropy energy, $E_{an}$, promotes the alignment of the magnetic moments along the 'easy' axis or 'easy' plane depending on what kind of (uniaxial) magnetic anisotropy is dominant in the system.

A multilayer film has different exchange constants depending on whether the exchange is developed in-plane or inter-plane. The nonmagnetic layers separating the magnetic layers may also contribute to the exchange constants between magnetic layers. As exchange coupling is a short-range effect the exchange constant inside each layer is much larger than the constant associated with the exchange interaction between the layers. Increasing the space between layers decreases the inter-layer exchange coupling but not the constant of magnetic anisotropy energy which is usually related to a long-range spin-spin interaction. There are some observations in $Co-Cu$ films that with an increase of the interlayer spacing the exchange constant strongly decreases while the constant in the anisotropy term fluctuates slightly [3].

In general the orientation of the magnetic moments depends on two angles $(\theta, \phi)$ associated with the in-plane and inter-plane rotation of the moments. However, as the in-plane exchange interaction is much stronger than the inter-plane exchange interaction, it is easier to cause a defect in the alignment of the magnetic moments of different layers than to create a defect inside a single plane and so the in-layer moments may be considered as a single domain whereas interlayer moments should not be. Therefore, as a first step, only inter-plane inhomogeneous magnetic structures created, assuming that all magnetic moments in the same layer align homogeneously, are considered.

With this assumption the relevant terms of the Hamiltonian associated with the interlayer magnetic structure are an interlayer exchange energy and the anisotropy energy. The competition between these two terms determines the interlayer structure of the magnetic multilayer film. The Euler-Lagrange equation for this model

$$-x_{n-1} + 2x_n - x_{n+1} + \beta \sin x_n = 0 \tag{1}$$

is a discrete version of the Sine-Gordon equation where $\beta$ is the ratio of the constant of anisotropy energy to the constant of exchange energy and $x_n$ is the orientation of the magnetic moments of the $n^{th}$ layer from the 'easy' axis. To solve this equation we apply the methods of Chaotic Dynamics. With such an approach [2], instead of solving the Sine-Gordon equation directly, we derive a 2D discrete map and investigate the trajectories of this map. The simple ferromagnetic alignment of the moments is a fixed point of (1) and does not depend on the value of $\beta$. However, there are always fluctuations associated with a finite number of layers that destroy any such alignment which make it impossible for this structure to exist. We find three characteristically different types of trajectories which may be classified as periodic, quasiperiodic and chaotic. These trajectories will correspond to the creation of three types of magnetic structures: periodic, quasiperiodic and chaotic, respectively.

It is found that the structures created depend on both the orientation of the magnetic moments in the first layer, $x_0$ and on the value of $\beta$. Two types of periodic magnetic structures are created at small values of $\beta$. The first is spin density waves frozen in space. In the second type of periodic structure the orientation of the magnetic moments perform a rotation as we move up through the layers. These rotations may have either a positive or a negative sign. In analogy with vortices in superfluid systems one may refer to this structure as a periodic structure of spin vortices. With the increase of the parameter $\beta$ from zero there initially arise frozen spin density waves, the period of which decreases as the value of $\beta$ increases. Then, at some value of $\beta$, there appear spin vortices which are periodically separated throughout the multilayer film creating a lattice. These spin vortices (see Fig 1) occur over a relatively small number of layers while their separation is very large. The first 35 layers have approximately the same orientation and are nearly perpendicular to the substrate, $x_0 \simeq 10^{-5}$. This region is schematically indicated by the three rows of disks immediately above the substrate in Fig 1. The deviation from the vertical axis progressively increases for the next 20 layers of the multilayer and spin rotation occurs. After this rotation there are about seventy-five layers with approximately vertically oriented magnetic moments and then the next spin vortex occurs. This structure is periodically repeated.

With further increase of the parameter $\beta$ the distance between the spin vortices decreases and also begins to fluctuate. When this distance becomes equal to the size of the spin vortex the quasiperiodicity is broken and some exotic, chaotic structures arise. In such structures, together with spin vortices, there are also incomplete spin rotations. Such structures arise only at large values of $\beta$ and may be equivalent to spin glasses arising in bulk magnetic samples.

In conclusion, we have found that in thick magnetic films associated with magnetic multilayers there may arise spin density waves, spin vortex lattices and possibly chaotic magnetic structures.

# References

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## Figure Caption

**Fig 1** The cross section of the magnetic multilayer film displaying a spin vortex arising in the 35th - 51st layers of a quasiperiodic magnetic structure with an approximate period of 90 magnetic layers.

$x_0 = 0.00001, \beta = 0.1$