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Stability under magnetic field of the two helices arrangement in a Eu(1 1 0) film

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Abstract

Single crystal Eu(1 1 0) films exhibit an atypical magnetic arrangement, different from the bulk three helices configuration: at low temperature, under zero field, only two magnetic domains are present since the magnetic helix that propagates along the in-plane [0 0 1] axis disappears below a given temperature. This paper presents the study of the stability of the magnetic domains under magnetic field using neutron scattering experiments and magnetisation measurements on a 375 nm thick Eu(1 1 0) film. The helix propagating along [0 0 1] is restored by the application of an external field along the [0 0 1] direction, which gives rise to a supplemental Zeeman contribution.

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Bulk rare earth exhibit complex magnetic phase diagram resulting from a competition between several temperature-dependent contributions to the magnetic energy [1]: exchange, crystal field anisotropy and magnetostriction (elastic and magnetoelastic energies)… Europium is an atypical light rare earth that is divalent to favour a half-filled 4f shell. Because of a smaller density of state at the Fermi level, bcc Eu exhibits a smaller exchange interaction and thus a much lower magnetic ordering temperature than its neighbour element gadolinium. The Eu^{2+} ions are in a $^{7/2}S$ ground state so that crystal field is small compared to the exchange.

Bulk Eu metal orders at $T_N = 90.4\,K$ [2] in an helical phase whose propagation vectors ($\boldsymbol{\kappa_1} = (\pm\tau\,0\,0)$, $\boldsymbol{\kappa_2} = (0\pm\tau 0)$ and $\boldsymbol{\kappa_3} = (0\,0\pm\tau)$) are parallel to the $\langle 1\,0\,0 \rangle$ axes of the bcc structure [3]. Three magnetic domains (D_1, D_2 and D_3) thus coexist, corresponding to three helices propagating along $\boldsymbol{\kappa_1}$, $\boldsymbol{\kappa_2}$ and $\boldsymbol{\kappa_3}$. Their populations P_1, P_2 and P_3 are equal to $\frac{1}{3}$ from T_N down to 4.2 K. The magnetic phase transition is accompanied by a tetragonal distortion of the crystal lattice [4].

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When a magnetic field is applied along a $\langle 100 \rangle$ direction, the stable structure is a helix structure propagating parallel to the field [5,6]. The two magnetic domains having a propagation vector perpendicular to the field decreased at the benefit of the third one. Actually, because the magnetic anisotropy of Eu is very small, it is therefore energetically favourable for the magnetic moments to turn normal to the field direction rather than for the helix to distort in its plane. When increasing magnetic field, a conical ordering of the moment is expected, with an apex angle of the cone becoming always smaller, leading finally to a ferromagnetic arrangement of the moments.

For a magnetic lanthanide film epitaxially grown on a substrate, the energy balance among alternative phases can be modified: (i) when the magnetic material is prevented from changing shape by its epitaxial clamping to the substrate; (ii) when the strains are likely to modify the magnetostrictive and/or the exchange energy.

Our general aim is to investigate the effect of epitaxy on the magnetic order in Eu films. Recently, Eu(1 1 0) films have been shown to exhibit an atypical magnetic arrangement, different from the bulk three helices configuration [7,8]: at low temperature, only two magnetic domains persist, since the magnetic helix that propagates along the in-plane [0 0 1] axis disappears below a given temperature. Moreover, the wave vectors of the helices propagating in bulk Eu along the [1 0 0] and [0 1 0] directions shift significantly from these directions, whereas those propagating along the [0 0 1] direction in the bulk remain along that direction. Both effects are film thickness dependent.

This paper presents a microscopic study of the stability of the magnetic domains under magnetic field in a 375 nm thick single crystal Eu(1 1 0) film. Results concerning the shift of the propagation vectors are presented elsewhere [8].

Using molecular beam epitaxy, a $Al_2O_3(1 1 \bar{2} 0)$ substrate is covered with a 50 nm thick Nb(1 1 0) buffer deposited at 800 °C. A specific study of the Eu growth process has shown that the further deposit of 15 nm Nb at 150 °C enables the epitaxial growth of a single crystal Eu(1 1 0) film presenting a single crystallographic domain, with the main crystal axis parallel to those of niobium [9]. From X-ray scattering measurements, the film exhibits a 0.25° mosaïc spread and a 59 nm coherence length along the growth direction. The Eu[1 1 0] axis presents a 1.4° angle respect to the Nb[1 1 0] axis. The lattice parameters at room temperature are similar to bulk europium, as expected from the large mismatch between Eu and Nb and from the large thickness of the film. However, the Eu cubic lattice is clamped to the underlying system and distorted in decreasing temperature below 175 K [8]. Below this temperature, the lattice parameter along the growth direction exhibits a continuous thermal decrease as in bulk Eu, whereas the in-plane parameters remain almost constant.

Magnetic structures have been determined as a function of field and temperature using macroscopic magnetization measurements (SQUID magnetometry) and neutron scattering experiments performed at the Laboratoire Léon Brillouin in Saclay (France) on the 4F2 triple axis instrument. The sample was placed in a cryomagnet with vertical field.

At 10 K and zero field, P_3 is always equal to zero but $P_1 \gg P_2$ or $P_2 \gg P_1$ depending on the magnetic history of the sample. This unexpected behaviour could be related to the occurrence of an angle between the Eu(1 1 0) planes and the Nb(1 1 0) ones. In fact, for a Eu(1 1 0) film presenting the same thickness but with Eu[1 1 0] parallel to Nb[1 1 0], P_1 and P_2 have been shown to be equal to 50% at low temperature whatever the history of the sample is [8].

Figs. 1a and b present the evolution of the intensity of the $\boldsymbol{\kappa}_2$ and $\boldsymbol{\kappa}_3$ satellites with magnetic field, starting from a magnetic configuration with $P_3 = 0$ and $P_2 \gg P_1$. When applying a magnetic field along the [0 0 1] direction at 10 K, the $\boldsymbol{\kappa}_2$ satellites suddenly disappear for a critical field: $H_a = 2.4$ T while the $\boldsymbol{\kappa}_3$ satellites are simultaneously restored. When decreasing again the field, the intensity of the $\boldsymbol{\kappa}_3$ satellites dropped to zero with an hysteresis effect for a critical field $H_d = 0.7$ T. For the same value of the magnetic field the D_2 magnetic domain is simultaneously restored. Note that the variation of the intensity at H_a and H_d are abrupt. The restoration of the D_3 domain at H_a and its disappearance at H_d are also observed