X-RAY RESONANT MAGNETIC REFLECTIVITY FROM Fe/Ce MULTILAYERS*

N. Jaouen[a], J.M. Tonnerre[b], D. Raoux[b], M. Müenzenberg[c]
W. Felsch[c], A. Rogalev[a], N. Brookes[a], H. Dürr[d]
and G. van der Laan[d]

[a]E.S.R.F., 6 rue Jules Horowitz, 38043 Grenoble Cedex, France
[b]Laboratoire de Cristallographie, CNRS
25 Avenue des Martyrs, 38042 Grenoble Cedex, France
[c]I. Physikalishes Institut, Universität, Göttingen
Bunsenstr. 9, 37073 Göttingen, Germany
[d]Daresbury Laboratory, Warrington WA4 4AD, Great Britain

(Received July 10, 2002)

We report on X-ray resonant magnetic reflectivity (XRMR) at the Ce L_2 and $M_{4,5}$ edges in an ex-situ grown Fe/Ce multilayer. We show that the measurement of the magnetic contribution to the intensities reflected at low angles allows us to investigate the profile of the Ce $5d$ and $4f$ magnetization. The calculated XRMR signals indicate that the Ce moments have a non-collinear structure.

PACS numbers: 71.27.+a, 75.50.Bb, 75.70.Cn, 78.70.Ck

1. Introduction

Dramatic differences in the physical properties of Ce metal are known to occur depending on its electronic and structural state. The $4f$ electron states being at the border between localization and itinerancy, both aspects can be found in the γ localized phase and in the α itinerant one of pure Ce metal. In the case of the Ce/Fe multilayers with a Ce thinner than about 45Å, cerium adopts the electronic structure of the α phase [1, 2]. This α-like state of Ce in the Fe/Ce multilayers is magnetically polarized at room temperature as demonstrated from XMCD measurements [1, 2] with an antiparallel orientation with respect to the Fe magnetization.

* Presented at the International Conference on Strongly Correlated Electron Systems, (SCES 02), Cracow, Poland, July 10–13, 2002.

In addition to chemical and orbital selectivity, XRMR provides spatially resolved informations on the magnetic ordering [3, 4]. In this contribution, XRMR is employed to investigate the $5d$ and $4f$ magnetization profile of Ce from a Ce/Fe multilayer.

2. Results

The experiment was performed at the European Synchrotron Radiation Facility (ESRF) on the ID12A and B beamlines [5] at the Ce L_2 and $M_{4,5}$ respectively. The experimental data were collected at room temperature in a geometry of the longitudinal magneto-optical Kerr effect (L-MOKE). Due to the ferromagnetic interlayer coupling, the magnetic contribution is bring out from the multilayer Bragg peak as an asymmetry ratio $R = (I^+ - I^-)/(I^+ + I^-)$, where I^+ and I^- are the intensities scattered for reversed in-plane magnetization of the sample while the helicity of synchrotron radiation is unchanged. Because of a suspected sample contamination, two nominally identical [Fe(30Å)/Ce(22Å)]×100 have been grown by ion-beam sputtering on Si(100) wafers [1]. The multilayers were characterized by X-ray reflectivity [3] and X-ray diffraction.

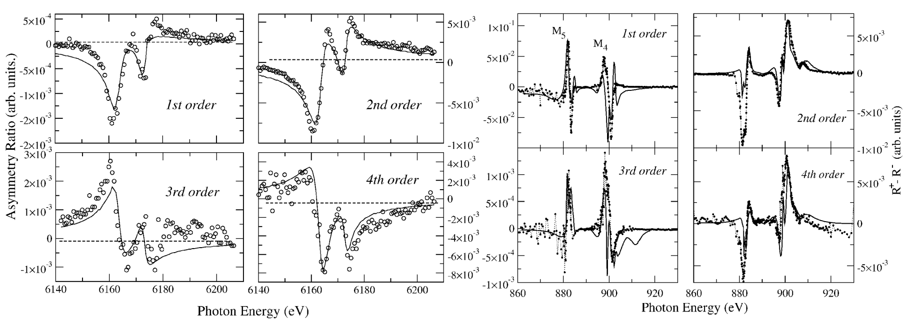

Fig. 1. Energy dependencies of the asymmetry ratios at the Ce L_2 (left) and $M_{4,5}$ (right) edges in the diffraction pattern of the Ce/Fe multilayer. Symbols show experimental values and full lines the simulations using the profile of polarization displays in Fig. 2.

Left part of Fig. 1 displays the energy dependencies of the four asymmetry ratios measured in the vicinity of the L_2 edge of Ce together with the results of the simultaneous refinement. The strong variation of the amplitudes of the R with the order of the superlattice Bragg peak, *i.e.* scattering vector k, is a direct evidence that the magnetic polarization is not steady throughout the Ce layers. In such a case, both the charge and the magnetic structure factors would have the same k dependance, so that their ratios would not exhibit any change with the order of the satellites and the R

neither. This energy dependence of the R, measured on low angle Bragg peaks, at the Ce L_2 edge were analyzed using the kinematic approximation, which proved to be correct even for the first low angle Bragg peak, following the model of De Bergevin [6]. More details on the refinement procedure are given elsewhere [3]. The 21.85Å thick Ce layer correspond to 7.8 hypothetical crystalline planes. In order to take into account the interfacial roughness the Ce atoms are considered to mix over one atomic plane at each interface. This model implies that the Ce sublayers extended over 25Å and are in average built with nine atomic planes: seven pure Ce and two mixed ones at both Fe interface containing 40% of Ce atoms. Finally, we consider that the average magnetization over the Ce sublayer will be equal to the values from XMCD measurements. The agreement between experiment and calculation in Fig. 1 is reasonably good though not perfect. Fig. 2(a) displays the corresponding profile of the $5d$ magnetic polarization per Ce atom which is found to be highly non collinear.

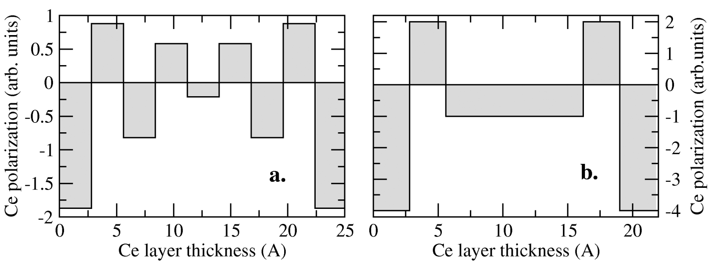

Fig. 2. Magnetic polarization profiles across the Ce sublayer of the $5d$ Ce states (a) and of the $4f$ Ce states (b).

In a similar way the asymmetry ratios were recorded at the Ce $M_{4,5}$ edge for the fourth first orders superlattice Bragg peaks. Due to huge absorption effects occurring at the Ce M edges, a magneto-optical approach was required in order to simulate the experimental asymmetry ratios. This approach describes the magneto-optical effects to first order in the magnetic field and derives the Fresnel coefficients for a multilayer based on medium and propagation matrices. The introduction of roughness effects [7] leads to good agreement with the experimental data, see right part of Fig. 1, for the M_4 edge. The amplitude difference at the M_5 edge may be due to the normalization of the experimentally obtained optical constants for the huge M edge resonance.

The shape and sign of these R can only be modelled if we assume a non uniform $4f$ magnetization profile across the Ce sublayer, the best model derived from our analysis is shown in Fig. 2b. Nevertheless this calculation depends very sensitive on the thickness of the individual probed layer (d_{Ce}=21.85 Å) and the magnetic amplitude of the two first layers.

3. Conclusion

We have used XRMR method to selectively investigate the profile of the $5d$ and $4f$ induced magnetic polarizations of Ce in Ce(22Å)/Fe(30Å) multilayers. For both states we found a strongly non collinear behavior associated with a decrease of the magnetic amplitude from the interface towards the inside of the Ce layer. However the extension of this magnetic order seems to be different for the $5d$ and $4f$ states. In agreement with XMCD experiments this magnetic ordering is located to the immediate interface with the Fe layer for the $4f$ states but extended far beyond in the case of the $5d$ states.

As previously reported [8,9], the H_2 introduction, leading to an increase of the lattice parameter and thus a relocalization of the Ce $4f$ states (γ-like Ce), induced a disappearing of this non-collinear order to a ferromagnetic one. This result indicates that this magnetic order may be an intrinsic property of Ce in Ce/Fe multilayers. No doubt this magnetic order is sensitive to the Ce $4f$ delocalization state, and we stress that strain effects in the Ce ultra-thin layer may be at the origin of a subtle change in the electronic configuration of Ce which is still α-like but close to a transition into the γ-like phase and, hence, very close to a magnetic instability according to the theoretical work of Min *et al.* [10].

Finally, we point out that a recent XMCD and MOKE study [11] showing a different magnetic response of the Ce $5d$ and Fe $3d$ magnetic moments in Ce/Fe multilayers to an external field could reflects the complex non-collinear magnetic structure in the Ce layers.

REFERENCES

[1] F. Klose *et al.*, *Phys. Rev.* **B50**, 6714 (1994).
[2] M. Finazzi *et al.*, *Phys. Rev. Lett.* **75**, 4654 (1995).
[3] L. Sève *et al.*, *Phys. Rev.* **B60**, 9662 (1999).
[4] D. Raoux *et al.*, *Acta Phys. Pol. A* **98**, 483 (2001).
[5] J. Goulon *et al.*, *Physica (Amsterdam)* **208B**&**209B**, 199 (1995); N. Dreschler *et al.*, *Rev. Sci. Instrum.* **68**, 1939 (1997).
[6] F. De Bergevin *et al.*, *Phys. Rev.* **B46**, 10772 (1992).
[7] E. Bontempi, N. Jaouen, J.M. Tonnerre, in preparation.
[8] N. Jaouen *et al.*, *Appl. Phys.* **A73**, 711 (2001).
[9] N. Jaouen *et al.*, submitted to *Phys. Rev.* **B**.
[10] B.I. Min *et al.*, *Phys. Rev.* **B34**, 369 (1986).
[11] M. Müenzenberg *et al.*, *J. Magn. Magn. Mater.* **220**, 195 (2000).