EUROPEAN SYNCHROTRON RADIATION FACILITY

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ESRF

Experiment Report Form

ESRF	**Experiment title:** "Study of room-temperature ferromagnetic coupling occurring at the Fe/(Ga,Mn)As buried interface by X-ray Resonant Magnetic Scattering"	**Experiment number**: HE2809
Beamline: ID08	**Date of experiment**: from: 11/02/2009 to: 17/02/2009	**Date of report**: 15/04/2009
Shifts: 18	**Local contact(s)**: Dr. Flora Yakhou-Harris	*Received at ESRF:*

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Report:

We measured an epitaxial Fe(x)/$Ga_{0.94}Mn_{0.06}As$(50nm)/GaAs sample, capped with 8 nm of gold. The Fe layer is in the bcc crystal form. The sample has two regions: one covered with 2nm of Fe, and another without the Fe, to be used as a reference. We acquired reflectivity energy scan at the Fe and Mn $L_{2,3}$ resonances at fixed angle, and θ-2θ angular scan at fixed energy, using circularly polarized light. The sample was magnetized applying a magnetic field in plane and the dichroism was measured by reversing the field direction before each scan. The full data set will be analyzed with the PPM software of Alessandro Mirone: in this report we will present the preliminary results obtained analyzing the dichroic oscillations of the θ-2θ angular scan, at different energies and temperatures. By tuning the photon energy on the Fe or Mn L_3 peak we had increased structural sensitivity to the Fe or Mn depth distribution. Moreover, with the use of circularly polarized light, we measured angular dichroic oscillations in the angular scan, that give information on the magnetization profile of the selected element.

On Figure 1 it is reported an angular scan a the Mn L_3 energy together with the dichroic (magnetic) component of the reflectivity. The oscillations of the reflectivity are related to the vertical distribution of the Mn, while the dichroic oscillations are related to the magnetization profile of the Mn. Similar spectra where measured at the Fe L_3 edge and off-edges.

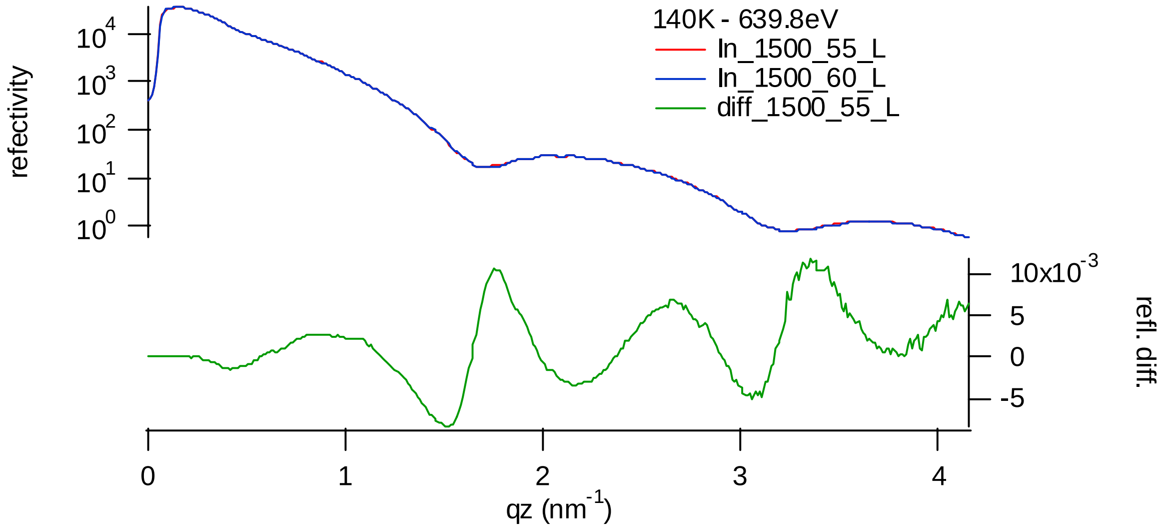

Figure 1 Reflectivity angular scan on Fe/(Ga,Mn)As at 140K and 639.8 eV (Mn-L_3 peak) (top); dichroism of reflectivity (bottom). The temperature is higher than the T_c=60K of (Ga,Mn)As, therefore the magnetic dichroic oscillations are due to the Mn magnetized by proximity effect with the Fe layer.

In the previous experiment made on ID08 (HE2515, year 2007), we found two energy-shifted Mn XMCD line shapes, attributed to the bulk, ferromagnetic (FM) (Ga,Mn)As and to the portion of Mn-ions that are magnetically coupled to the Fe layer with the magnetization antiparallel (AP) to the latter. On Figure 2 are reported the XAS/XMCD spectra of pure (Ga,Mn)As (blue), of the surface oxides (yellow) and of the AP Mn, magnetized by proximity effect with the Fe. In the right panel, the L_3 edge of the XMCD of the FM and AP Mn-ions, are magnified to show the energy shift between the two peaks.

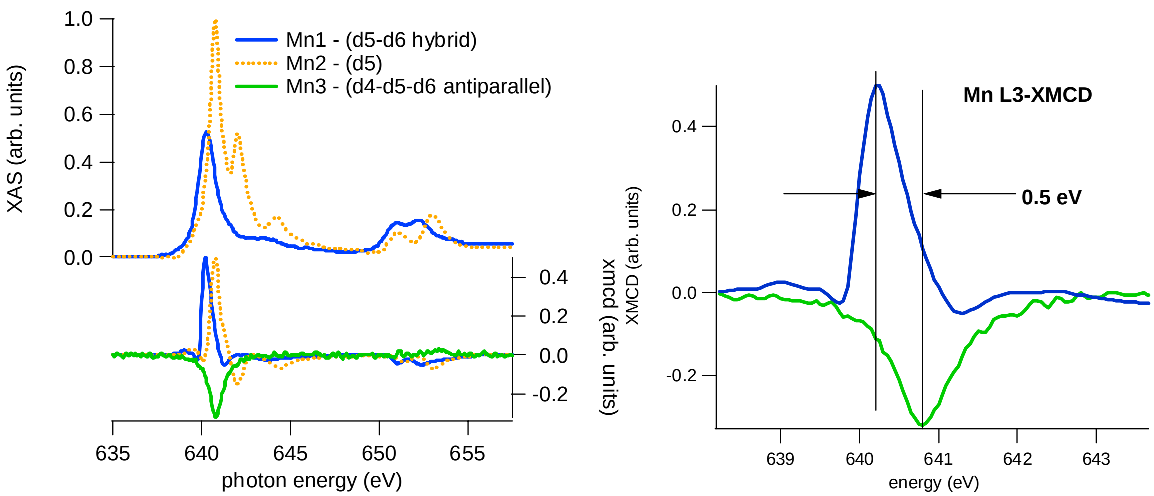

Figure 2 XAS/XMCD (left) template spectra of pure (Ga,Mn)As (blue), of surface Mn oxides (yellow) [Kronast, PRB **74**, 235213 (2006)] and experimental XMCD of the Mn magnetized at room temperature by proximity effect with the Fe over-layer (green); (right) magnification of the Mn XMCD of the ferromangetic bulk (Ga,Mn)As (blue) and of the Mn magnetically coupled by proximity effect with the Fe in the antiparallel direction (spectrum from ID08 HE2515 experiment).

The precise knowledge of the XMCD footprint of the two Mn populations (FM and AP) allowed us to selectively probe one of the two magnetic phases of the Mn by tuning the photon energy on the XMCD peak of the selected phase: the FM bulk (E=640.2 eV), or the AP interfacial (E=640.7 eV). Despite the small change in photon momentum, due to the 0.5 eV change in the photon energy, we observed strong variations in the dichroic oscillations of the angular reflectivity scans. We can thus infere that the depth distribution of the AP and FM magnetic phases are different. Moreover by measuring below and above the Curie temperature (T_c) of the bulk (Ga,Mn)As, we observed the appearance/disappearence of a frequency component of the dichroic reflectivity oscillations that can be clearly attributed to the bulk FM (Ga,Mn)As film.

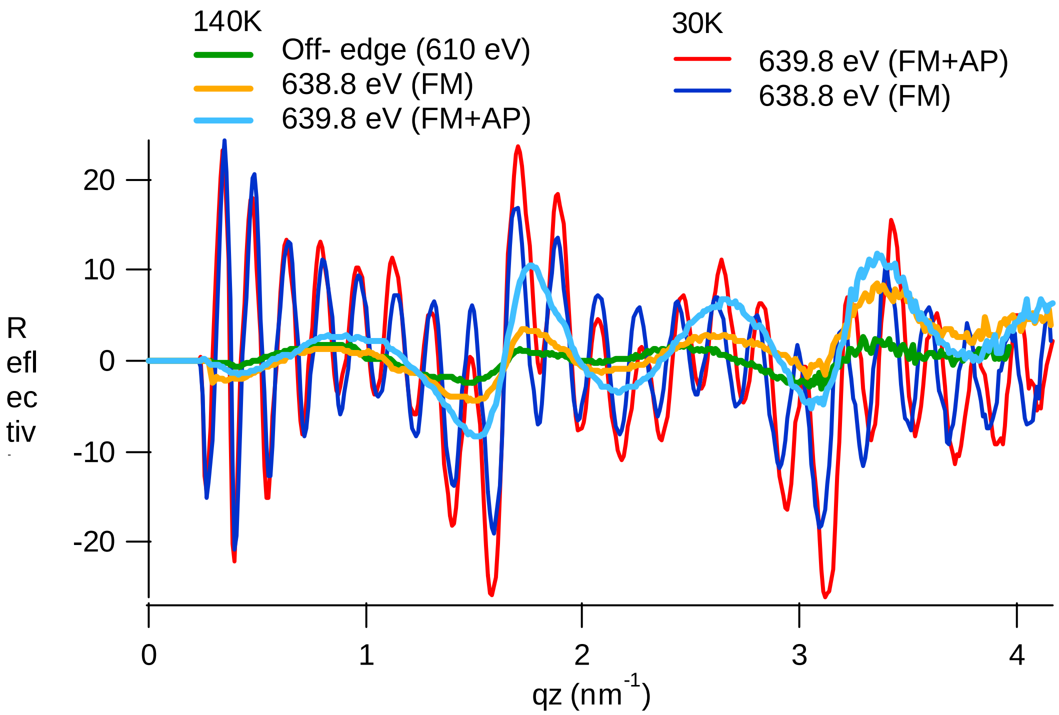

Figure 3 Dichroic angular *θ-2θ* reflectivity scan of Fe/(Ga,Mn)As below and above the (Ga,Mn)As T_c and at different energies.

The Figure 3 collects a serie of angular dichroic scan above (140K) and below (30K) T_c for two different energies on the Mn-L_3 edge and off resonance, versus the wave-vector exchanged. It is clearly visible that the high frequency oscillation that is present at 30K, disappears above T_c: it correspond to the thick (Ga,Mn)As FM film. The lower frequency component is always present, because the AP magnetic layer is present up to room temperature. The green curve is the off-resonance scan, and should not have any oscillations: the residual modulation is due imperfect reproducibility of the agular position (on the order of ±0.01°).

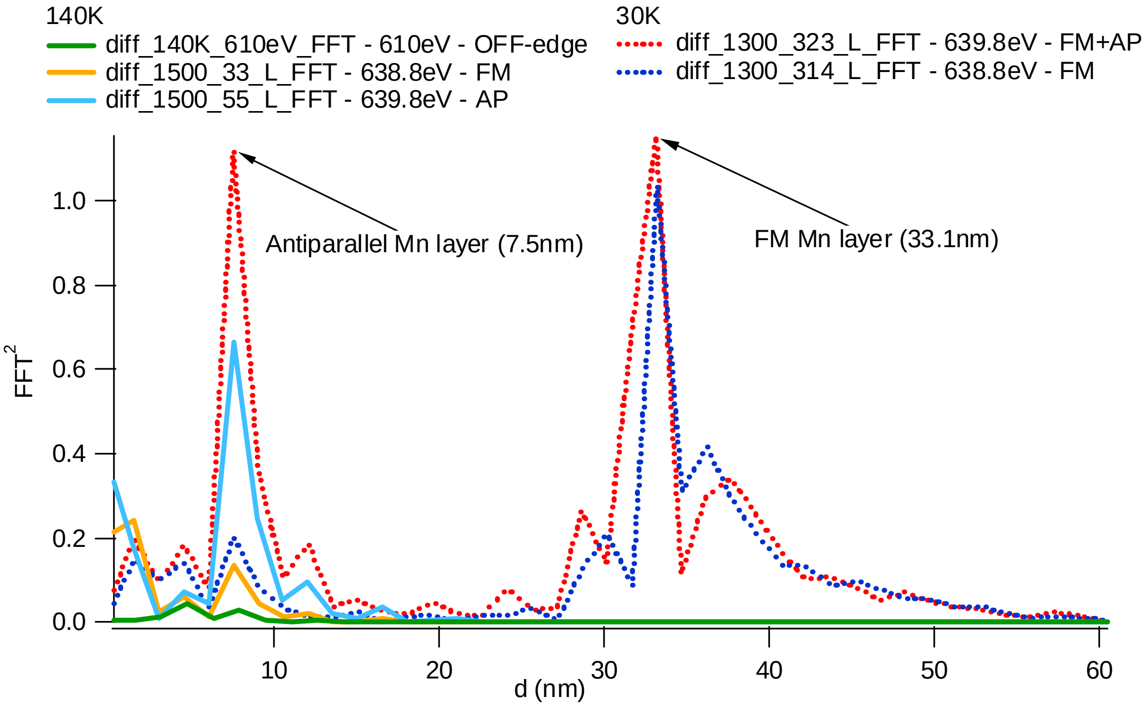

Figure 4I Fourier transform power spectrum of the θ-2θ reflectivity dichroic scan.

In order to estimate the thicknesss of the magnetic layers, we calculated the Fourier power spectrum of the dichroic reflectivity curves. The frequencies in the space of wave-vectors can be related to the thicknesses of the magnetic layers by the condition of constructive interference of the reflected beams. In Figure 4 we reported the power spectrum of each dichroic reflectivity curve of Figure 3: we can observe two peak at 8 nm and 33 nm, corresponding to the interfacial AP layer and to the bulk FM (Ga,Mn)As film. The 33 nm peak is present only at 30 K (below T_c). At 140K we have only the 8 nm peak, that is suppressed as far as the photon energy is moved away from the AP XMCD peak (E=639.8 eV).

The preliminary data analysis allow us to identify the presence of two magnetic layers and to attribute them to the two magnetic phases present in the (Ga,Mn)As film, plus the Fe FM overlayer. In order to properly draw the magnetic depth profile, with the exact relative positions of the magnetic layers, it is necessary to take into account also the phases of the oscillations, and the simulation of the full data set is required.

The experiment allowed us to directly measure the thickness of the AP layer, magnetized by proximity effect with the Fe, that was the main objective of the proposal. The rough estimations of the length range of the proximity effect (about 8nm) made during the previous XAS/XMCD experiment on ID08 (HE2515) were confirmed.

Francesco Maccherozzi