ESRF	**Experiment title:** Valence band orbital polarization in III-V ferromagnetic semiconductors	**Experiment number**: HE-2707
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Report:

Introduction. The (III,Mn)V ferromagnetic semiconductors are of fundamental interest for studies of hole-mediated ferromagnetism and as test systems for development of novel spin devices. Their magnetic properties arise from hybridization between the half-filled 3*d* shell of the dilute substitutional Mn ions and the 4*p* valence states of the III-V host. The large spin-orbit splitting of these valence states gives rise to giant anisotropic effects in magnetoresistance, as well as large and tunable magnetocrystalline anisotropies [1]. Here, we directly probe the temperature-dependent 4*p* orbital polarization of a series of (III,Mn)V thin films using As *K* edge x-ray magnetic circular dichroism. X-ray absorption at the *K* edge probes transitions from 1*s* core states to valence states with *p* character, and the difference in absorption for opposite circular polarizations yields the projected orbital magnetic moment per atom of these states along the incident beam direction.

Experimental details. The studied 200nm thick (In,Ga,Mn)As films, with varying In concentration, were grown on InP(001) substrates using molecular beam epitaxy. The Mn concentration was around 8%, and the Ga:In ratio was either 60:40 or 40:60. The substrate temperature during growth was around 200^{o}C. Post-growth, the films were annealed in air at 190^{o}C in order to optimize their magnetic properties by out-diffusion of interstitial defects. Magnetometry and anomalous Hall effect measurements confirmed a ferromagnetic transition temperature T_C of around 70K in the optimally annealed films, and also showed that the films are single-phase with no metallic ferromagnetic inclusions. The As *K* edge x-ray absorption and XMCD measurements were performed on beamline ID12 at ESRF using the total fluorescence yield signal, with the external magnetic field either perpendicular or nearly parallel (~15^{o}) to the sample surface.

Results. Figure 1(a) shows the normalized magnetization-averaged As *K* edge x-ray absorption spectrum and the XMCD spectrum. The XMCD appears as a sharp peak at the onset of the absorption edge, which is approximately twice as large as in our previous studies [2], due to the higher hole density in the present samples. Applying the XMCD sum rules to the data yields an orbital magnetic moment of around 0.002 μ_B per As ion. This corresponds to an orbital moment of between -0.1 μ_B and -0.2 μ_B per valence band hole. For the annealed films, similarly large XMCD signals were obtained for both 40% and 60% In content.

In contrast, for unannealed samples, the As *K* XMCD was scarcely measureable due to the compensation of holes by interstitial defects.

Figure 1(b) shows hysteresis loops measured by sitting at the photon energy corresponding to the peak of the As XMCD signal, and obtaining the difference in absorption for left- and right-circularly polarized light as a function of magnetic field. The As polarization tracks the net magnetization of the film, showing a sharp switch between ±0.3T, and with a saturation value that decreases with increasing temperature up to T_C (70K). Above T_C, a paramagnetic response of the XMCD to the external magnetic field is observed.

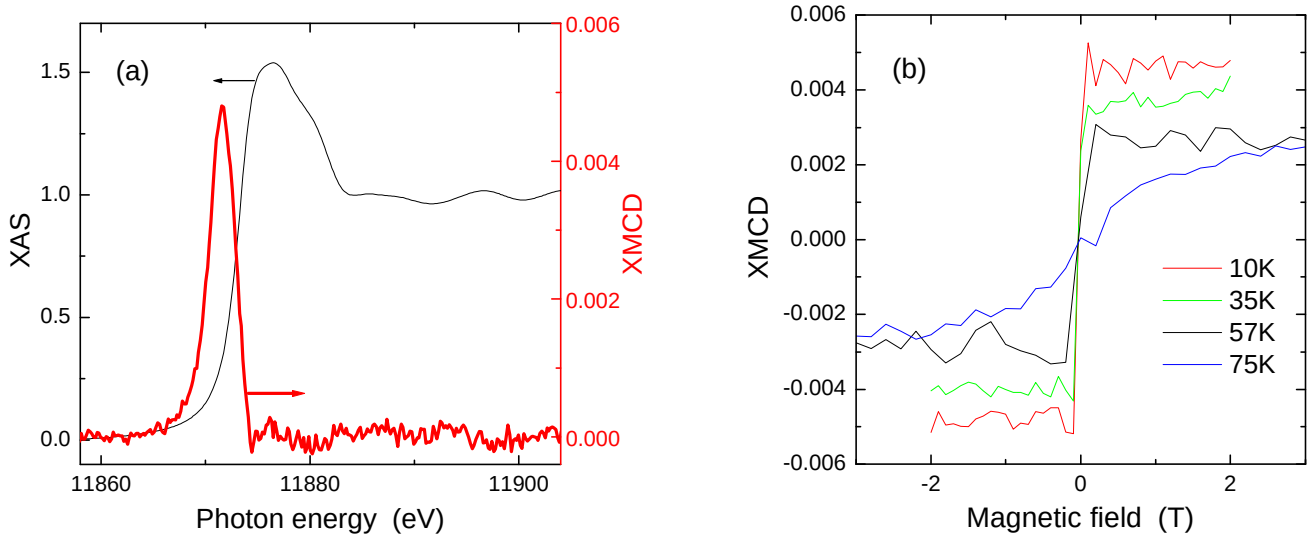

Figure 1. (a) As K edge x-ray absorption spectrum (thin line, left axis) and XMCD (thick line, right axis) of an annealed 200nm (In,Ga,Mn)As film; (b) peak XMCD versus magnetic field at various temperatures.

Summary and outlook. Our results have shown the presence of a significant polarization of As 4*p* orbitals in (In,Ga,Mn)As ferromagnetic semiconductor thin films. The magnitude of the As *K* edge XMCD depends on the hole density of the films, and follows the net magnetization as a function of magnetic field and temperature. Detailed analysis is underway in order to compare the obtained magnetic moments to band structure calculations. It is also of interest to investigate the dependence of the orbital polarization on hole density in more detail, by controlled co-doping. By comparing the As polarization to the Mn 3*d* localized magnetic moments measured by Mn $L_{2,3}$ XMCD [3], it will be possible to obtain detailed information on the character and hybridization of states near the Fermi level in the III-V ferromagnetic semiconductors, which is crucial for realistic modelling of spin and spin-orbit coupling phenomena in these materials.

References

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