	Experiment title: Sm 4*f* alignment in SmN and across SmN/GdN heterojunctions	Experiment number: HC-684
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Background to the study

This $M_{4,5}$-edge XAS/XMCD study was conceived to determine the depth-dependent Sm 4*f*-shell spin alignment across a thin SmN layer exchange coupled to Gd across an epitaxial GdN/SmN interface. This pair, GdN and SmN, are unique.

- They are intrinsic ferromagnetis semiconductors, already a rare quality.[1]
- They are epitaxi-compatible, a (NaCl) structure and lattice matched to within 1%.
- They have strongly contrasting saturation moments, 7μ_B per Gd but only 0.03 μ_B for Sm due to an near cancellation on the 4*f*-shell orbital and spin magnetic moments,
- and a factor of 1000 difference in their coercive fields.[2]

The saturation moment in SmN gives it the smallest ferromagnetic magnetisation of all known stoichiometric compounds. Even that is not well understood, for a free Sm^{3+} ion is expected to have a moment of ~0.8 mB, and in the crystal field of SmN it has a moment of 0.45 mB.[2] The very small moment of SmN prevents a full investigation by SQUID measurements, especially in a superlattice in which it is masked by the enormous GdN moment. Nonetheless we have considerable SQUID data showing the influence of the SmN layers on the GdN magnetisation. Here, however, we have been able to concentrate on the details of spin and orbital alignment in SmN layers exchange-coupled to GdN.

The structures show device promise because of the 10^3-fold contrast in the coercive fields of GdN and SmN, so to advance that programme it was of interest also to follow the Gd and Sm spin alignments in layers that had been decoupled by an exchange-blocking LaN layer. There are further fundamantal challenges to model the Sm spin alignment in this very unusual system. We determined by studies (on ID12) at the $L_{2,3}$ edge that the marginal domination of the orbital moment in SmN determines that the net magnteisation is directed antiparallel to the spin magnetic moment.[3] Thus the Zeeman interaction aligns the 4*f* spins antiparallel to the field in bulk SmN. In contrast the purely spin moment in GdN aligns the spin moment parallel to the field. The GdN/SmN interface exchange-dominated interaction is directed in turn opposite to the Zeeman alignment acting on SmN. The Sm alignment direction is then expected to rotate through the SmN layer. It is this issue that we began to explore, acessing the 4f-dipolar interrogation provided by $M_{4,5}$-edge XMCD; our earlier L2,3-edge results signal the alignment only indirectly by the probing the 5*d*-shell alignment.

Experiments performed

XMCD and XAS measurements were performed in fluorescence (TFY) and electron (TEY). TFY measurements are compromised by self absorption, distorting the specrta, but we nonetheless used it to trace the spin alignment and provide first-approximation hystresis studies on both Gd and Sm edges. In view of the small escape depth of relevence for TEY measurements the more detailed study was restricted to the Sm edge on 10 nm of SmN top layers grown over GdN with and without a LaN exchange-blocking layer. The requirement for a passivating cap further led to relatively weak TEY signals, dictating the interpretation based on the use of the distorted TFY to support the weaker TEY spectra.

Measurements were performed primarily at the lowest temperature available, ~10 K and to magnetic fileds to 4T. TEY and TFY results (Fig. 1 upper panel)) show that the Sm alignments in the GdN/LaN/SmN structure are determined by the Zeeman term alone, with the Sm spin magnetic moment antiparallel to the applied field. That suggests, among other things, that a 0.5% concentration of Gd would reduce the net magnetisation to zero.

Turning to data on a GdN/SmN sample (Fig.1 lower), we see immediately that the TEY, though of the same sign as in a decoupled film, is smaller by a factor of 6. TFY is smaller by a factor of only 3, and more importantly has the opposite sign to both the TEY signal in this coupled layer and the TFY signal in a decoupled layer. It's clear that the bulk of this coupled layer has an alignment determined by the Gd-Sm exchange interaction across the interface, but that close to the free SmN surface, which is probed by TEY, it shows a Zeeman-interaction dominated alignment.

We are presently developing a modelling proceedure for the spin rotation thruogh the SmN layers, and will very soon submit a publication based on these and complementary ID12 data at the $L_{4,5}$ edge. The beamtime was extraordinarily successful, and has allowed us to advance toward both an understanding of spin alignments in the complex exchange + Zeeman determined system and to work toward proof-of-concept devices.

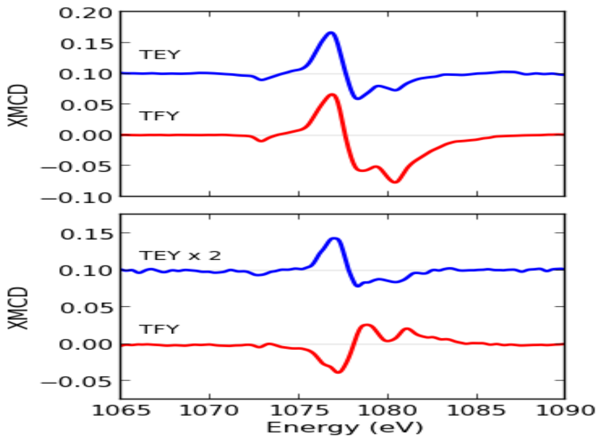

Figure 1. Sm M_5-edge XMCD in a GdN/SmN heterojunction with (upper panel) and without (lower panel) a LaN exchange blocking layer. The Gd-Sm exchange near the GdN interface reverses the fluorescence yield (TFY) spectrum in the exchange-coupled sample. The electron yield (TEY) spectrum is weakened but not reversed, establishing that the Gd influence does not fully control the spin orientation through the entire SmN layer.

[1] F. Natali et al, Prog. Mat. Sci. **58**, 1316 (2013).
[2] C. Meyer et al, PRB Phys. Rev. B **78**, 174406 (2008).
[3] Anton et al, PRB Phys. Rev. B **87**, 134414 (2013).