	Experiment title: XLD, XMCD and element specific hysteresis of the superdilute magnetic semiconductor Gd:GaN	**Experiment number**: HE-2250
Beamline: ID 12	**Date of experiment**: from: 30.08.2006 to: 05.09.2006	**Date of report**: 10.10.2006
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Report:

First, we measured the x-ray linear dichroism (XLD) at the Ga K-edge and at the Gd L_3-edge on hexagonal and cubic GaN films grown on sapphire. The results for the Ga K-edge are summarized in Fig. 1. Comparing the XLD signal to the previously measured XLD at Mn-doped GaN samples the signal clearly corresponds to Ga in the wurtzite structure (upper panel in Fig.1, see E. Sarigainnidou et al., PRB **74**, 041306 (2006).) For

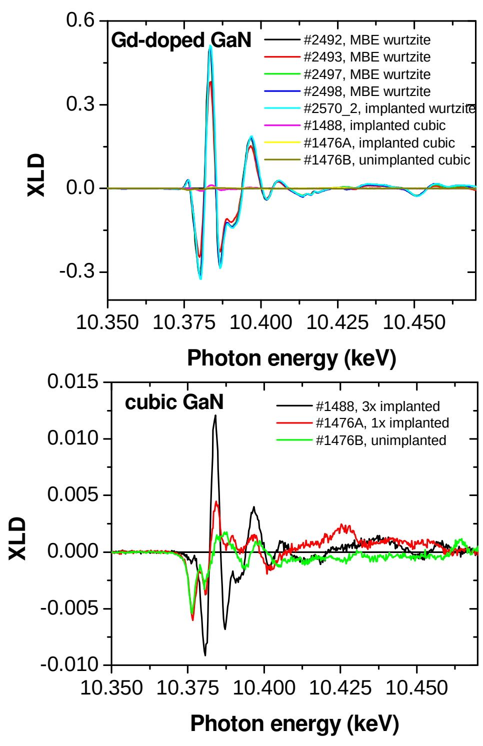

Figure 1: Normalized XLD spectra at the Ga K-edge of various Gd doped and ion-implanted GaN samples. The lower panel shows a magnification of the XLD spectra measured on cubic GaN.

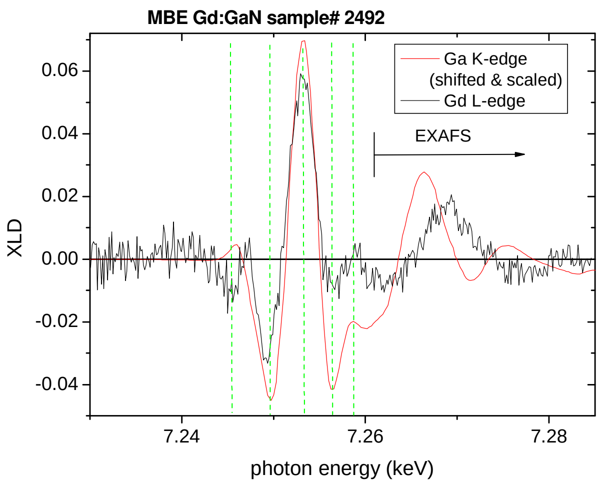

Figure 2: Normalized XLD spectrum at the Gd L3-edge of a wurtzite Gd-doped GaN. For comparison the shifted and scaled Ga K-edge XLD is shown and all peaks can be identified indicated by the dashed lines.Thus, Gd exists in the same local crystal environment as Ga.

the cubic GaN samples the situation is different (Fig. 1, lower panel). The XLD signal is strongly reduced and shows peaks which are different for the unimplanted sample. This remains unchanged after a first Gd-implantation step but changes to a weak but clear wurtzite-like XLD after three subsequent implantation steps. Obviously, the Gd-ion-implantation leads to a partial recrystallization of the cubic GaN making it more wurtzite-like. The magnetic properties as measured with a SQUID magnetometer are much weaker in the cubic GaN phase compared to the wurtzite phase, Since these experiments provide a direct measure of the local crystal symmetry a more detailed analysis together with simulations can give more information about the role of the crystal field in altering the magnetic properties. Further XLD experiments were carried out on the Gd L-edge of the wurtzite sample with the highest Gd doping of about

$10^{19}/cm^3$. Experiments at the Gd L-edges of the other samples (50 and 1000 times less Gd, respectively) were unsuccessful since such tiny amounts of Gd could not be detected. Fig. 2 shows the XLD at the Gd-L_3 edge together with the shifted and scaled XLD recorded at the Ga K-edge. It is obvious, that both elements are in the same local crystal environment, i.e. at least some of the Gd is on substitutional Ga lattice sites. Since simulations can provide the amplitude of the XLD signal, such an analysis can provide the fraction of the Gd atoms being at substitutional sites. The XLD measurements provide us with the local structural information for all our samples. On the other hand, since the circular light is not 100\% polarized, there will always be a residual linear dichroism visible for the wurtzite samples making the reliabe detection of a magnetic circular dichroism at the Ga K-edge more difficult.

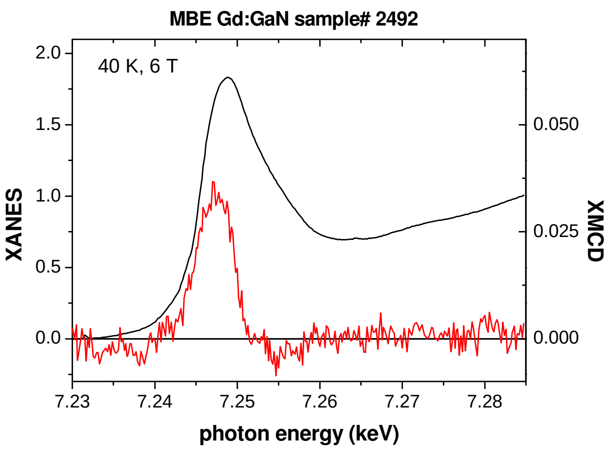

Figure 3: Absorption and XMCD spectra for the wurtzite GaN sample with the highest Gd concentration of about $10^{19}/cm^3$. A clear small XMCD signal is visible at the Gd L3-edge at 40 K.

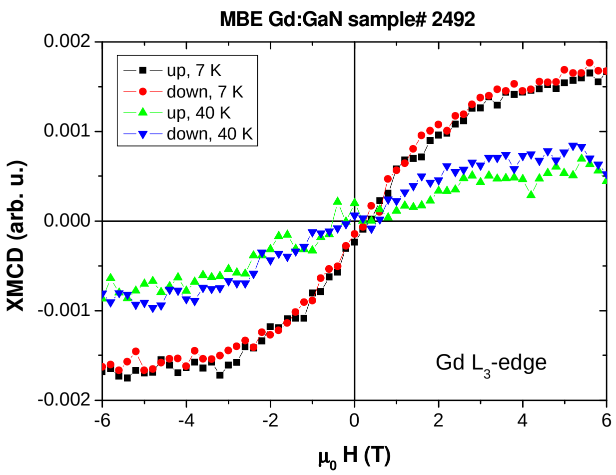

Figure 4: Element specific hysteresis at the Gd L3-edge recorded at 7 K and at 40 K.

In a second step x-ray magnetic circular dichroism (XMCD) measurements were carried out at one implanted and one MBE-grown wurtzite GaN sample followed by element specific hysteresis measurements recorded at the Ga and at the Gd edges at 7 and 40 K, respectively. Fig. 3 shows the Gd L_3-edge of the MBE grown sample at 40 K. Both, the helicity of the light and the magnetization were reversed to rule out artefacts. The XMCD spectrum at 7 K is of the same shape but about a factor of two bigger in size. Since also the background of the absorption spectrum is increased at 7 K, it is difficult to say if this increase is due to the temperature or partially due to the background normalization. Nevertheless, an increase of a factor of two from 40 K compared to 7 K at 6 T is consistent with previous SQUID measurements. The Gd-edge at the Gd-ion-implanted sample was too weak to record any reliable XMCD signal. Fig. 4 shows the element specific hysteresis recorded at the Gd-L-edge at 7 K and at 40 K at magnetic fields up to 6 T. The field was ramped up and down and no opening of the hysteresis is visible within the uncertainty of the measurement. At 7 K thius is consistent with SQUID measurements where a paramagnetic-like behavior with a shallow opening of the loop is observed. The data at 40 K clearly differ from SQUID measurements which show a more squarish hysteresis. Thus, the magnetic behavior observed by SQUID is quite unlikely to originate from the Gd alone. Unfortunately, we were not able to record a conclusive XMCD signal at the Ga K-edge. For both the Gd implanted and the MBE grown sample we could record a tiny XMCD signal at the Ga K-edge (not shown), but it was much smaller than the residual XLD which does not reverse with the magnetic field. Thus we could not record any conclusive XMCD at the Ga K-egde. This is consistent with the concentration dependent SQUID measurements suggesting an average polarization per Ga atom of about 0.003 μ_B (S. Dhar et al., PRL **94**, 037205 (2005)). The tiny XMCD-like signal of both samples strongly differed showing peaks at different energies. Nevertheless, we tried to record element specific hysteresis loops at the Ga K-edge at one of the small XMCD features where the residual XLD appeared to be small. For both samples there was essentially no signal detectable in the noise (not shown). For the implanted sample the only interesting feature was a clear increase of the XMCD signal at 5 T which has the same sign for both field directions. The origin of this artefact is unclear so far. In summary, the XMCD and hysteresis measurements will help us to determine an upper limit of the possible polarization of the GaN host crystal.