# Soft X-ray Magnetic Circular Dichroism Study on Gd-doped EuO Thin Films

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## Introduction

EuO is one of the rare ferromagnetic semiconductors. In the stoichiometric case it has a Curie temperature of 69 K [1]. Slightly Eu-rich EuO is metallic at low-temperature and the magnetic transition is accompanied by a metal insulator transition (MIT) with 10 orders change of resistivity [2]. An applied magnetic field shifts the MIT temperature resulting a colossal magnetoresistance (CMR) [3]. The essentially complete spin polarization of charge carriers after electron doping [4] makes EuO a very attractive candidate for fundamental research in the field of spintronics. Here we report on the growth of Gd-doped EuO thin films and the enhancement of $T_C$ upon Gd doping.

## Experimental

The samples were grown *in-situ* by means of MBE. To prevent the formation of oxides higher than EuO we set the Eu evaporation rate such that it is much in excess compared to the oxygen rate. At the same time, we kept the substrate temperature sufficiently high so that a distillation process occurs in which excess Eu is re-evaporated into the vacuum. In this way we successfully prepared Gd-doped EuO films with Gd concentrations up to 11%. The x-ray absorption (XAS) spectra were recorded using the total electron yield method. For the magnetic circular dichroism (XMCD) the samples were placed in a magnetic field of about 0.2 T a permanent magnet.

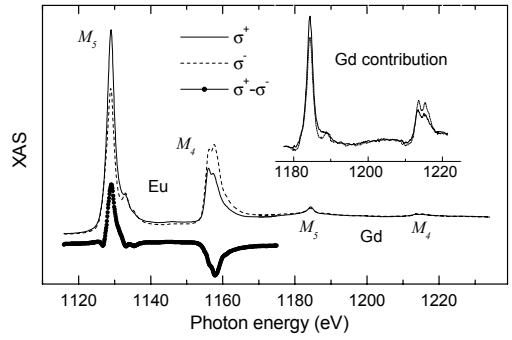


Figure 1. Eu and Gd $M_{4,5}$ XMCD spectra of a 3.7% Gd-doped EuO sample at 20 K Inset: net Gd contribution.

## Results

We investigated the magnetic properties of samples with different doping concentrations by means of XMCD. Fig.1 shows the Eu and Gd $M_{4,5}$ XMCD spectra of a 3.7% Gd-doped EuO sample recorded at 20 K using circularly polarized x-rays with the photon spin parallel ($\sigma^+$) and antiparallel ($\sigma^-$) to the magnetic field direction. The difference spectrum, i.e. the XMCD, is proportional to the sample magnetization. Fig. 2 shows $T_C$ as a function of the Gd doping concentration. Starting from around 69 K for undoped EuO, $T_C$ increases rapidly upon Gd doping and reaches a maximum of about 170 K at 4% Gd-doping. To our knowledge, this is the highest $T_C$ reported so far for a EuO system. For higher Gd concentrations $T_C$ slowly decreases again.

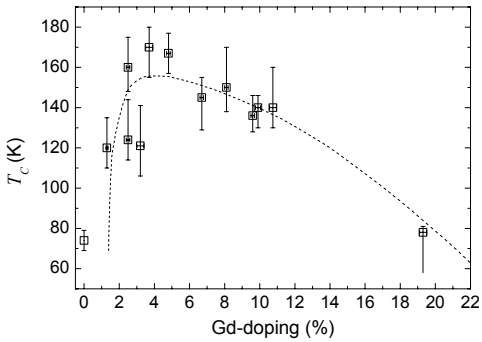


Figure 2. Doping dependent Curie temperature ($T_C$). The dotted line represents the result of a mean-field calculation.

The doping dependence of has also been calculated by Mauger using a mean-field approximation [1] depicted as dashed line in Fig.2. The calculation assumes a critical Gd concentration of about 1% below this concentration. It is energetically favorable for the ``extra'' electrons to remain localized around the Gd impurities, forming a bound magnetic polaron. Above the critical Gd concentration, free carriers are available and $T_C$ increases accordingly. The maximum in $T_C$ is caused ba an instability of the ferromagnetic configuration with respect to a spiral structure. The agreement between experiment and theory appears to be satisfactory.

An open question so far is whether the Gd spins are coupled to the Eu spins, and if so, whether they are parallel or antiparallel aligned. The resulting net Gd contribution to the spectra is shown in the inset of Fig.1, one can easily conclude that the Gd and Eu *4f* spins are aligned parallel. We have investigated the Gd *4f* spin alignment for various doping levels up to 11%, and found in all cases that it is parallel to the Eu spins, in agreement with the calculation of Mauger.

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