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Journal of Magnetism and Magnetic Materials 226–230 (2001) 1174–1176

Journal of magnetism and magnetic materials

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# The magnetic structures of $Ho_xTm_{1-x}$ thin film alloys

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**Abstract**

Single-crystal alloys of $Ho_xTm_{1-x}$ were grown using the molecular beam epitaxy technique. The components of the magnetic moments along the *c*-direction and in the basal plane were obtained using neutron diffraction, and the magnetic structures of this system have been determined. The results were compared with calculations based on a mean-field model, and the theoretical predictions are in good agreement with the experimental results. The existence of the penta-critical point at $x_c = 0.325$ and $T_c = 67.85$ K, which was also predicted by the mean-field model was confirmed by the experimental results. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* Rare earth; Magnetic structures; Mean-field theory

Bulk Ho orders magnetically below $T_N \sim 132$ K and its magnetic structure is a basal-plane helix, changing to a cone phase on cooling below $T_C \sim 22$ K [1]. In contrast, bulk Tm has a *c*-axis longitudinally modulated magnetic structure below $T_N \sim 58$ K [2]. In this work, the temperature dependence of the magnetic moments in the basal plane and along the *c*-axis of the HCP lattice were obtained for the $Ho_xTm_{1-x}$ alloys, using neutron diffraction. The results were compared with mean-field calculations performed by Jensen, and the magnetic phase diagram was determined.

The $Ho_xTm_{1-x}$ samples were grown by MBE with $\sim 10\,000$ Å of thickness, following the technique described in Ref. [3]. The neutron diffraction experiments were similar to those described in Cowley et al. [4]. After correcting the integrated intensities of the magnetic reflections for the instrumental resolution [5], the values of $\langle gJ_\perp(q)\rangle$, $\langle gJ_z(q)\rangle$ and $\langle gJ_z(0)\rangle$ were obtained. The transition temperatures between the magnetic phases were labelled as $T_{AB}$, where A and B represent the observed magnetic phases, which were cone (Co), basal-plane helix (H), tilted helix (T), cycloid (C) and longitudinally modulated (L). Details about the temperature dependence of the wave vectors transfer, and the complete work, will be presented in Ref. [6].

In the mean-field model [7], the magnetic structures were calculated using the virtual crystal approximation, and the exchange coupling constants between the different kinds of ions were constructed from a linear interpolation between the constants in pure Ho, $\mathcal{J}_{Ho}(ij)$, and pure Tm, $\mathcal{J}_{Tm}(ij)$, scaled with the appropriate factors:

$$\mathcal{J}_{A\text{-}B}(ij) = (g_A - 1)(g_B - 1)\left[ x\frac{\mathcal{J}_{Ho}(ij)}{(g_{Ho}-1)^2} + (1-x)\frac{\mathcal{J}_{Tm}(ij)}{(g_{Tm}-1)^2}\right], \quad (1)$$

where each of the indices A and B denotes either a Ho or a Tm ion.

The crystal-field and the coupling parameters used in the present calculations are given in Tables 1 and 2, respectively. The parameters for Tm are those obtained by McEwen et al. [8]. In the case of Ho [9], the

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0304-8853/01/$ - see front matter 
PII: S0304-8853(00)01308-1

Table 1
The crystal-field parameters used in the mean-field calculations in units of meV

| $B_l^m$ | $B_2^0$ | $B_4^0$ | $B_6^0$ | $B_6^6$ |
|---|---|---|---|---|
| Ho | 0.024 | 0.0 | $-9.56\times10^{-7}$ | $9.21\times10^{-6}$ |
| Tm | −0.096 | 0.0 | $-9.2\times10^{-6}$ | $8.86\times10^{-5}$ |

Table 2
The inter-planar exchange coupling coefficients given in units of meV

| $J_n$ | $J_0$ | $J_1$ | $J_2$ | $J_3$ | $J_4$ | $J_5$ | $J_6$ |
|---|---|---|---|---|---|---|---|
| Ho | 0.263 | 0.100 | 0.010 | −0.029 | −0.005 | 0.008 | −0.004 |
| Tm | 0.098 | 0.057 | −0.022 | −0.025 | −0.010 | −0.002 | 0.0 |

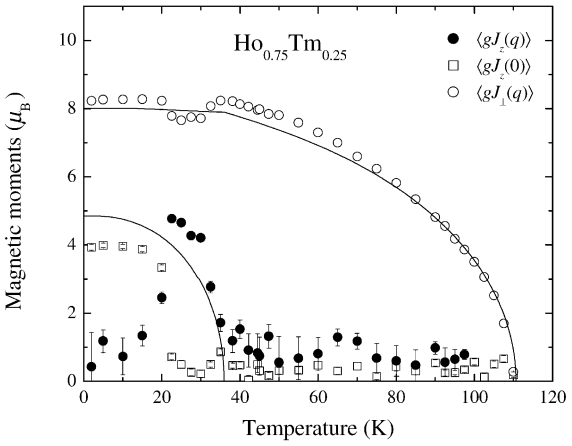


Fig. 1. The ordered magnetic moments for $Ho_{0.75}Tm_{0.25}$. The open circles represent the basal-plane moment, the solid circles the modulated $c$-axis moment and the open squares the ferromagnetic $c$-axis moment. The solid lines represent the results of the model.

temperature dependence of the exchange parameters is simplified by using the parameters presented in Table 2.

Fig. 1 illustrates the temperature dependence of the components, $\langle gJ_\perp(q)\rangle$, $\langle gJ_z(q)\rangle$ and $\langle gJ_z(0)\rangle$, for the $x = 0.75$ alloy ($g$ is the Landé factor, and $J_\perp$, $J_z$ is total angular momentum in the basal plane and along the $c$-direction, respectively). The lines represent the results of the mean-field calculations and the points represent the transition temperatures obtained from the experiment. At the lowest temperature, $\langle gJ_z(0)\rangle$ and $\langle gJ_\perp(q)\rangle$ are non-zero and the structure is a cone with an angle of $\sim 26^\circ$. At $T_{TCo} = 20\,K$, $\langle gJ_z(q)\rangle$becomes non-zero,

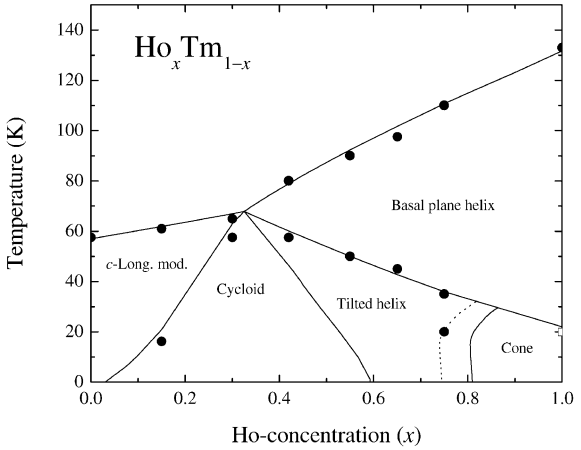


Fig. 2. The magnetic phase diagram of the $Ho_xTm_{1-x}$ alloys. The closed circles show the transition temperatures observed and the lines represent the model predictions. The dashed line shows the result calculated with a small modification of the original model to account for the cone phase.

while $\langle gJ_z(0)\rangle$ is negligible because of a first-order transition from the cone to a tilted-helix phase. Above a higher temperature $T_{HT}$ 35 K, $\langle gJ_z(q)\rangle$ is negligible therefore, the structure is a basal plane helix. The transition to a paramagnetic phase occurs at $T_{PH} = 110\,K$.

The magnetic phase diagram for the $Ho_xTm_{1-x}$ alloys is illustrated in Fig. 2. For a pure film of Ho, the cone phase is suppressed as shown in Refs. [3,10]. The mean-field model predicts correctly the values of $T_{HT}$, $T_{CL}$, $T_{LP}$ and $T_{PH}$, for all compositions, and the existence of the penta-critical point at $x_c = 0.325$ and $T_c = 67.85\,K$. However, for $x = 0.75$, a slight modification of the anisotropy terms in the model would be necessary to account for the first-order transition from the tilted helix to the cone phase (indicated by the dashed line on Fig. 2). For $x = 0.42$ and 0.55, the mean-field model also predicts the presence of a cycloid phase. The transitions from a cycloid to a tilted helix cannot be observed directly, so there is more uncertainty about the determination of this phase boundary. This is also valid for the calculations, as the position of this phase line depends sensitively on the values of the fourth and sixth rank axial anisotropy parameters, which are also the most uncertain ones. Experimentally, the ordered $c$-axis moment behaves more like that obtained using a modified model, which suppresses the transition to the cycloidal phase, indicating that the most likely possibility is that the structure stays in the tilted phase at all temperatures below $T_{HT}$. The mean-field model predicts correctly the transition temperatures $T_{CL}$ and $T_{PL}$, for the $x = 0.30$ and 0.15 alloys, and for $x = 0$. Therefore, the model is in good agreement with the experiment.

Financial assistance from the EPSRC in the UK, CAPES in Brazil, and the EU through the LIP programme is gratefully acknowledged.

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