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PHYSICAL PROPERTIES OF Gd-Sc SINGLE CRYSTAL RANDOM ALLOYS

R. J. Melville (1), S. B. Palmer (1), J. B. Sousa (2), J. M. Moreira (2), C. Carvalho (2) and R. P. Pinto (2)

(1) Dept. Of Physics, University of Warwick, Coventry CV4 7 AL
(2) Centro de Fisica, Universidade do Porto, Porto, Portugal

Abstract. We have measured the elastic constant \( C_{33} \), the resistivity and the thermopower of single crystal samples of 4 Gd-Sc alloys. The behaviour of these physical properties are interpreted in the light of recent neutron diffraction studies and present a range of unusual features.

Interest in the magnetic properties of the Gd-Y and Gd-Sc random alloys has been revived in recent years due largely to the successful application of short wavelength neutrons (0.5 Å) to probe the magnetic structures [1, 2]. It is clear that the competition between c-axis ferromagnetic order favoured by Gd and basal plane helimagnetic order favoured in the alloys richer in Y or Sc, together with the very low magnetic anisotropy and random distribution of the magnetic ions, is responsible for the complex magnetic phase diagram close to 70 at. % Gd. Here we concentrate mainly on the Gd-Sc alloy series.

We have used ultrasonic measurements of the elastic constants and associated ultrasonic attenuation, together with electrical resistivity and thermopower measurements to characterize four single crystals, \((\text{Gd}_{64}\text{Sc}_{36}, \text{Gd}_{68}\text{Sc}_{32}, \text{Gd}_{75}\text{Sc}_{25})\) which were grown by the MSU, Birmingham University, G.B. We will discuss the results in conjunction with the underlying information on the magnetic structures provided by neutron diffraction experiments, and start from the sample richest in scandium \((\text{Gd}_{64}\text{Sc}_{36})\). In figure 1 we show the temperature dependence of \( C_{33} \), the elastic constant associated with longitudinal ultrasonic propagation along the hexagonal c-axis, \( \rho_c \) (\( \rho_c \) is the c-axis electrical resistivity) and \( S_c \) (where \( S \) is the thermopower). All these properties exhibit a sharp minimum at the Néel temperature \( T_N \approx 140 \text{ K} \), where the basal place helix onsets. Important fluctuation effects extend to temperatures well above \( T_N \) (\( T \geq 1.5 T_N \)) and inspection of the \( \rho_c \) data reveals a change in the critical behaviour at temperatures close to \( T_N \).

In the helimagnetic phase the neutron studies indicate a turn angle \( \omega \) decreasing smoothly from \( \sim 33.6^\circ \) at \( T_N \) down to \( \sim 26.1^\circ \) at 30 K. Below 30 K, \( \omega \) is temperature independent reflected by a pronounced decrease of \( \rho_c \) with decreasing temperature. This freezing of \( \omega \) contrasts with the case of Gd-Y alloys of comparable composition, where \( \omega \) goes smoothly to zero as \( T \) decreases in the helimagnetic phase [2]. A weak anomaly, of unknown origin, is noticed in the \( \rho_c \) curve at \( T \approx 70 \text{ K} \).

For \( \text{Gd}_{68}\text{Sc}_{32} \), \( C_{33} \) is more complicated reflecting the neutron evidence that the purely basal plane helix only extends from \( T_N \approx 154 \text{ K} \) down to \( \sim 56 \text{ K} \). Below 56 K, \( \omega \) stabilises at \( \sim 20.6^\circ \) and a moment is developed along the c-axis producing a conical helix. The elastic constant \( C_{33} \) decreases rapidly at 56 K, and is accompanied by a rapid increase in the ultrasonic attenuation \((\alpha_{33})\). This may be due to either a magnetoelastic interaction where the canting angle is very sensitive to the c-axis lattice parameter producing strong coupling between the c-axis longitudinal wave and the conical structure, or to a domain wall effect arising from the domains associated with the c-axis moment.
Figure 2 shows $C_{33}(T)$ and $d\rho_c / dT$ for Gd$_{72}$Sc$_{28}$, where sharp minima are again observed in $C_{33}$ and $d\rho_c / dT$ at $T_N = 167$ K. In the paramagnetic phase close to $T_N$ an upward curvature develops in $d\rho_c / dT$, similar to earlier observations in Gd-Y alloys [4] where the effect is attributed to the critical enhancement of short-range $c$-axis order. As $T$ approaches closer to $T_N$ a sudden crossover is observed in $d\rho_c / dT$, attributed to short-range basal plane order leading to the onset of the helical structure at $T_N$. This crossover occurs so close to $T_N$ that the transition looks almost first order.

The simple basal plane helix phase extends in this sample down to $\sim 113$ K below which high values of $\alpha_{33}$ can again be attributed to magnetoelastic coupling in the conical helix phase. A small step anomaly is observed in $d\rho_c / dT$ (with $\rho$ itself being continuous), indicating a second-order transition. The sudden increase in $d\rho_c / dT$ just below $113$ K is attributed to the onset of a $c$-axis ferromagnetic moment, which decreases $\rho$, producing therefore a higher $d\rho / dT$ value. The helix finally disappears at about $60$ K where a canted ferromagnet develops with a strongly temperature dependent canting angle. This transition is associated with a small step in $d\rho / dT$, but in the opposite sense to that observed at the basal-conical helix transition. This can be explained if we recall that $\omega$ gives a positive contribution to $d\rho / dT$ through $d\omega / dT$. As $d\omega / dT > 0$ just above $60$ K and $d\omega / dT$ vanishes in the low temperature phase, we should observe a corresponding negative step in $d\rho / dT$. In the canted phase the $\alpha_{33}$ and $C_{33}$ slowly recover their high temperature values, due either to increasing anisotropy confining the moments more rigidly to the cant direction or to domain changes. Below $\sim 13$ K the $C_{33}(T)$ curve shows clear pre-transitional mode softening to an as yet undetermined phase.

$C_{33}(T)$ for Gd$_{75}$Sc$_{25}$ is shown in figure 1. This alloy composition has not yet been subjected to neutron investigation, but comparison with the two previous samples highlights certain similarities. There is a region of high ultrasonic attenuation, from 171 K to 153 K, possibly a conical spiral and followed by a canted ferromagnetic phase below 153 K. What is not yet clear is the structure of the initial ordered phase just below 178 K, and the low temperature phase ($T < 35$ K).

In summary, we see no positive evidence of the Ferro I ordered magnetic phase in Gd-Sc (although precursor $c$-axis fluctuation effects are observed in $d\rho_c / dT$) or of turn angles falling smoothly to zero as observed in Gd-Y alloys [1, 2]. The system appears to be just as finely balanced energetically as Gd-Y, but with a more noticeable tendency to develop a $c$-axis moment in the cooperative magnetic phases.

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