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DOUBLE FERROMAGNETISM IN SINGLE CRYSTAL Gd_{0.75}Y_{0.175}Sc_{0.075} ALLOY

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Abstract. – Magnetization, electrical resistivity, thermal expansion and specific heat measurements on Gd_{0.75}Y_{0.175}Sc_{0.075} single crystal show two anomalies at the transition temperatures and two different Curie-Weiss regimes leading to double ferromagnetism. The variations of the two transition temperatures with a uniaxial stress have been measured.

The alloy series between the element Gd and nonmagnetic elements Sc, Y and Lu have been the subject of considerable interest in recent years. At high Gd concentrations the Gd-Sc, Gd-Y and Gd-Lu polycrystal alloys exhibited normal ferromagnetism. However, the results of detailed measurements on single crystals showed two transition temperatures suggesting the new magnetic ordering phenomenon [1]. The Gd_{0.75}Sc_{0.25} single crystal alloy showed antiphase domain ferrimagnetic structure between the two transition temperatures [2]. The Gd_{0.70}Y_{0.3}, Gd_{0.8}Lu_{0.2} and Gd_{0.75}Y_{0.175}Sc_{0.075} single crystals showed two sharp anomalies at the transition temperatures and the low isofield magnetization data for the a-axis samples showed two different Curie-Weiss regimes leading to double ferromagnetism [3, 4].

Gd metal exhibits only one ordered phase of ferromagnetism and one phase transition at T_c = 293 K. The easy direction of magnetization lies along the c-axis from T_c down to the spin reorientation temperature T_1 \approx 235 K and the surface of a c-axis cone below T_2. Neutron diffraction measurements showed that between T_1 and T_2, the spin orientation indicates the long-wavelength orientation fluctuations around the c-axis and only the average easy axis of magnetization is parallel to the c-axis. Rare earth metals and alloys are known as the most typical materials in which the RKKY indirect exchange model is applicable. With the addition of the nonmagnetic elements Sc, Y and Lu to the magnetic element Gd, it would be expected that the magnetic interactions between Gd elements decrease in accord with a simple dilution theory, and also that the periodicity of the long-wavelength fluctuations around the c-axis near T_c be disturbed by the nonmagnetic elements. Sc metal has the same hcp crystal structure as Y and Lu, and the slightly smaller atomic volume than Y and Lu. It is interesting to see if adding some Sc to Gd-Y might change some magnetic behavior. We report here the results of detailed measurements of magnetization, electrical resistivity, thermal expansion, specific heat and effect of uniaxial stress on the transition temperatures on Gd_{0.75}Y_{0.175}Sc_{0.075} single crystal.

In figure 1, we give the low isofield magnetization data for the directions of applied magnetic field for Gd_{0.75}Y_{0.175}Sc_{0.075} single crystal. The magnetic moment increase with decreasing temperature in Curie-Weiss fashion down to the T_c of 216 K. Then the concave-upward rise of the moment along the direction except for the c-axis continues in a second Curie-Weiss manner down to the second Curie temperature T_c^1 of 188 K, a result which suggest double ferromagnetism. A model was suggested in reference [1] which places the moments on the surface of a cone around the c-axis at T_c with the basal plane component random down to T_c^1 below which simple ferromagnetism exists. The falloff of the moment except for the a-axis below T_c^1 is thought to be a manifestation of growing anisotropy with the basal plane becoming the easy direction of magnetization. The temperature difference of 28 K between T_c and T_c^1 is wider than those of 12 K for Gd_{0.75}Sc_{0.25}, 2.5 K for Gd_{0.8}Lu_{0.2} and 8.5 K for Gd_{0.75}Y_{0.175}Sc_{0.075}. Figure 2 shows the results of the temperature derivatives of the electrical resistivity (A), thermal expansion coefficient (B) and specific heat (C). Sharp anomalies at both ordering temperatures are observed. The anomaly at T_c shows a \lambda-type

![Fig. 1. Low isofield magnetization vs. temperature for Gd_{0.75}Y_{0.175}Sc_{0.075} single crystals.](image-url)
second-order phase transition and the anomaly at \( T_1 \) shows a sharp spike first-order phase transition. The effects of uniaxial stress on the transition temperatures \( T_c \) and \( T^1_c \) along the direction parallel to \( c \)- and \( a \)-axes for Gd\(_{0.75}\)Y\(_{0.175}\)Sc\(_{0.075}\) single crystal are shown in figure 3. The variations of the \( T_c \) when subjected to a uniaxial stress up to 360 bar applied along the \( c \)- and \( a \)-axes are \((-2.8 \pm 0.1) \times 10^{-3} \) deg bar\(^{-1} \) and \((0 \pm 0.1) \times 10^{-3} \) deg bar\(^{-1} \), respectively. Using the molecular field model, the variations of the exchange interaction with the \( c \) and \( a \) crystallographic parameters are obtained from the experimental results and the values of the elastic moduli. We obtain \( \partial (I/k)/\partial \ln c = 192 \) K and \( \partial (I/k)/\partial \ln a = 57 \) K. The rates of change of the \( T^1_c \) with a stress applied along the \( c \)- and \( a \)-axes are \((-3.2 \pm 0.1) \times 10^{-3} \) deg bar\(^{-1} \) and \((1.8 \pm 0.1) \times 10^{-3} \) deg bar\(^{-1} \), respectively. The rates of change of the \( T_c \) for Gd metal and the \( T_N \) for Dy metal, respectively [5, 6].

Using a simplified band model, Kaino and Kasuya investigated the role of the nonlinear effect of the s-f exchange interaction on the magnetic properties of Gd alloys [7]. They pointed out that the nonlinear effect and easy axis anisotropy stabilize the antiphase domain structure or cone structure near the highest ordering temperature. The magnetic structure of double ferromagnetism is that of the modification of the cone structure. The phase transition at \( T_c \) arises from the suddenly change of easy direction from \( c \)- to \( a \)-axis with decreasing temperature.

Fig. 2. – Temperature derivatives of the electrical resistivity \( (A) \), thermal expansion coefficient \( (B) \) and specific heat \( (C) \) vs. temperature for Gd\(_{0.75}\)Y\(_{0.175}\)Sc\(_{0.075}\).

Fig. 3. – Variation with uniaxial stress of the \( T_c \) and \( T^1_c \) of a single crystal of Gd\(_{0.75}\)Y\(_{0.175}\)Sc\(_{0.075}\).