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Antiphase Domain Structure in Gd-Y Alloys

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Magnetization and low field ac susceptibility measurements have been made on $Gd_{70}Y_{30}$ single crystal alloys. Low isofield susceptibility data for the *c*-axis sample exhibit a sharp peak at the highest ordering temperature, which suggests the existence of the antiphase domain structure in the *c*-axis ferromagnet region with basal-plane disorder. The antiphase domain structure is easily supressed by the applied field of about 20 Oe in the susceptibility measurement.

§I. Introduction

Gadolinium is the only rare earth that exhibits normal ferromagnetism over its entire ordering range. Neutron diffraction measurements[1] showed that between the Curie temperature (293 K) and the spin-reorientation temperature (235 K), gadolinium has long-wavelength spin-orientation fluctuations and only the average easy direction of magnetization is parallel to the hexagonal *c*-axis. The magnetic ordering of the rare-earth metals and alloys is believed to take place by a long range oscillatory indirect exchange interaction of the RKKY-type between the 4f electrons vir polarization of the conduction electrons. According to the theory the nearest-neighbor interaction is ferromagnetic and the next-nearest-neighbor interaction is antiferromagnetic. The addition of nonmagnetic element Y to the magnetic element Gd would be expected that the ferromagnetic interactions decrease more than antiferromagnetic interactions. Hence, the Curie temperature of this alloy should decrease in accord with simple dilution theory and the magnetic ordering should become antiferromagnetism (herical) at sufficiently high concentrations of the nonmagnetic component Y. For the most part, experimental results are in agreement with these predictions.[2),3)] However, there are some differences in the detailed behavior of the magnetic phases for these alloy systems near the highest ordering temperature.

Legvold *et al.*[4),5),6)] investigated the Gd-Y single crystals and found a new magnetic ordering phenomena in the Gd-rich ferromagnetic alloys. The low isofield magnetization data for the *a*-axis samples showed two different Curie-Weiss regimes, which suggests double ferromagnetism. The transport and ultrasonic studies[7),8)] for Gd-Y alloys showed the precise region of the magnetic phases. Recently, the first neutron-diffraction and magnetization studies[9] of Gd-Y alloys have shown a phase diagram in the vicinity of 30 at.% Y. The results showed that in the upper ferromagnetic region (ferro-I) the *c*-axis is easy direction with basal-plane disorder, while the lower ferromagnetic region (ferro-II) has a canted ordered moment, and herical-ferro II phase boundry marks a boundary where the propagation vector *q* (and therefore the turn angle of the spiral) of the modulated structure goes smoothly to zero. The magnetic structure is easily suppressed by the applied field of 39 Oe in the magnetization measurement. It is interesting to study the lower field susceptibility measurements in the ferro-I and ferro-II region.

Here we present the results of the magnetization and low field ac susceptibility for $Gd_{70}Y_{30}$ single crystal alloys which exhibit the ferromagnetism including the ferro-I and ferro-II phases.

§2. Sample Preparation

The single crystals used in this study were prepared in bulk form starting with the highest purity Ames Laboratory polycrystalline Gd and Y metals. The alloys were arc melted together into small buttons in a purified argon atomosphere. The single crystals were grown by the annealing process described by Nigh.[10] Back reflection Laue X-ray picture revealed clear spots, indicating a good quality crystal of the hcp structure. The single crystal for $Gd_{70}Y_{30}$ was cut out from the same ingot used previously by Legvold *et al.*[4] For measurement of magnetization and low field ac susceptibility, the single crystals were cut into rectangular parallelepipeds, $3\times2.5\times5$ mm^3, with the long dimension oriented along the crystallographic axis to be placed in the direction of the magnetic field.

§3. Experimental Results

The magnetization was measured in the temperature range from 4.2 K to room temperature by means of vibrating-sample magnetometer. Figures 1 and 2 show the magnetization per gram versus temperature at different applied field for the *a*- and *c*-axes of $Gd_{70}Y_{30}$, respectively. We can see the two ordering temperatures of T_c and T_c^1 up to 100 Oe. It appears that 200 Oe of applied field is sufficient to eliminate the conical phase and that about 1 kOe is needed to overcome the free pole domain effects and anisotropy effects.

Low field ac magnetic susceptibility was measured by means of a standard Hartshorn bridge circuit at the various ac magnetic fields of 1 kHz in frequency. The cryostat including the sample holder was shielded by shield demagnetizer which was made of fourfold permalloy vessel to remove the effect of the Earth's field of about 0.4 Oe at Shimane University. The behaviour of the ac susceptibility curves was indepen-

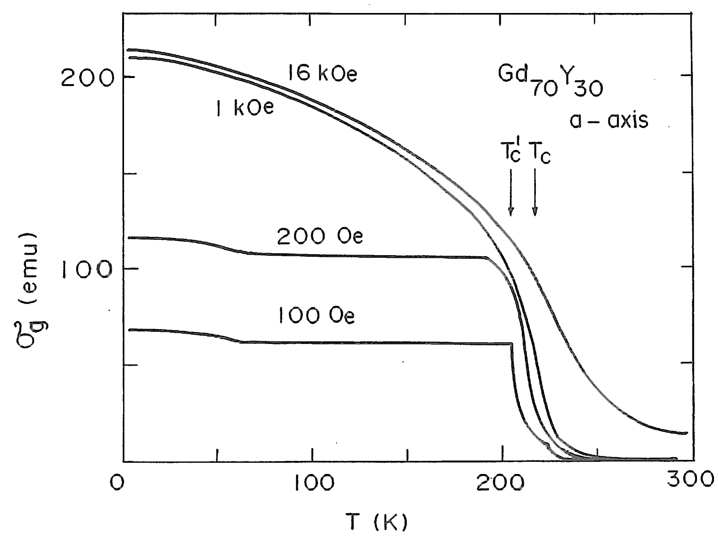

Fig. 1. Isofield magnetization vs temperature for $Gd_{70}Y_{30}$ along the *a*-axis.

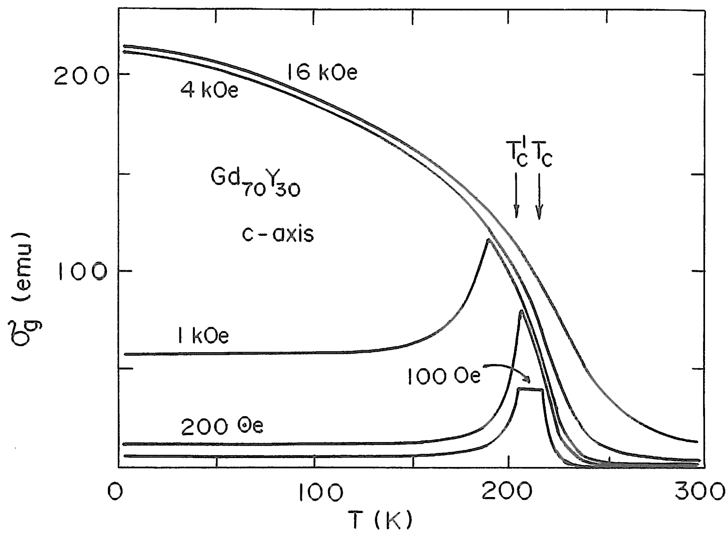

Fig. 2. Isofield magnetization vs temperature for $Gd_{70}Y_{30}$ along the *c*-axis.

dent of the frequency from 200 Hz to 23 kHz.

Figures 3 and 4 show the results of the isofield ac susceptibility normalized by the value of the susceptibility at T_c versus temperature for the *a*- and *c*-axes of $Gd_{70}Y_{30}$ single crystals, respectively. The applied ac magnetic fields are 20, 3, 0.2 and 0.05 Oe in amplitude. The *a*- and *c*-axes curves at 20 Oe are similar to the curves reported previously[4),5)] by Legvolt *et al.* for $Gd_{70}Y_{30}$ alloy which were obtained from the

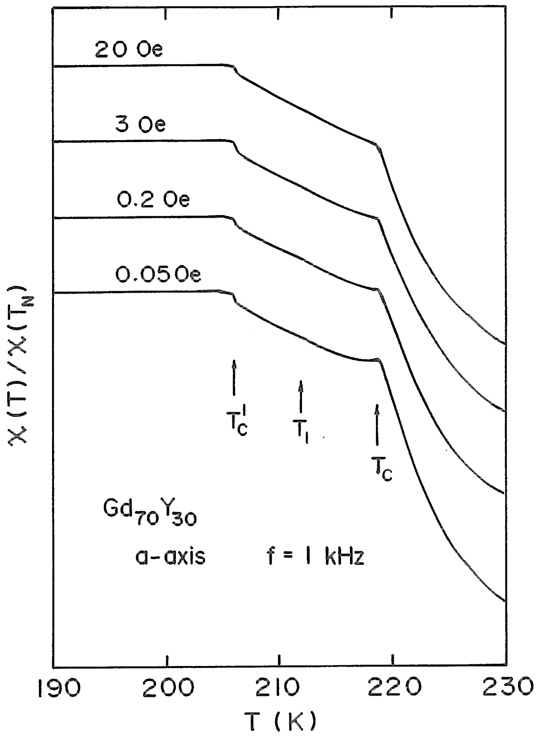

Fig. 3. Low isofield ac susceptibility vs temperature for $Gd_{70}Y_{30}$ along the *a*-axis at various ac magnetic fields.

magnetization measurements at 39 Oe by means of a vibrating-sample magnetometer. The ac susceptibility shows Curie-Weiss growth with dcreasing temperature for both *a*- and *c*-axes samples down to T_c of 218.8 K. Below T_c the a-axis susceptibility at 20 Oe shows a second concave upward Curie-Weiss growth down to a transition temperature T_c^1 of 205.5 K, a result which suggests a continuing disorder in the basal plane. On the other hand, the *c*-axis data at 20 Oe shows a constant value between the temperature T_c and $T_c^{\ 1}$, indicating an ordered *c*-axis component of the moment. A model of double ferromagnetism was suggested in Ref. 4 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 basal-plane helical phase exists.[9] All the isofield susceptibility curves for the *a*-axis show the same type of behavior. However, the susceptibility curves for the *c*-axis in applied ac magnetic fields below 7 Oe show a sharp peak at the highest ordering temperature. The *c*-axis curve at 0.05 Oe shows a small maximum at a T_1 of 212.1 K between the transition temperature of T_c and T_c^1. The observed drop in *c*-axis susceptibility between T_c and T_1 suggests the existence of the antiphase domain structure of double ferromagnetism. The moments have a squaring off of the *c*-axis component in which several atomic layers having *c* components up (cones open upward)

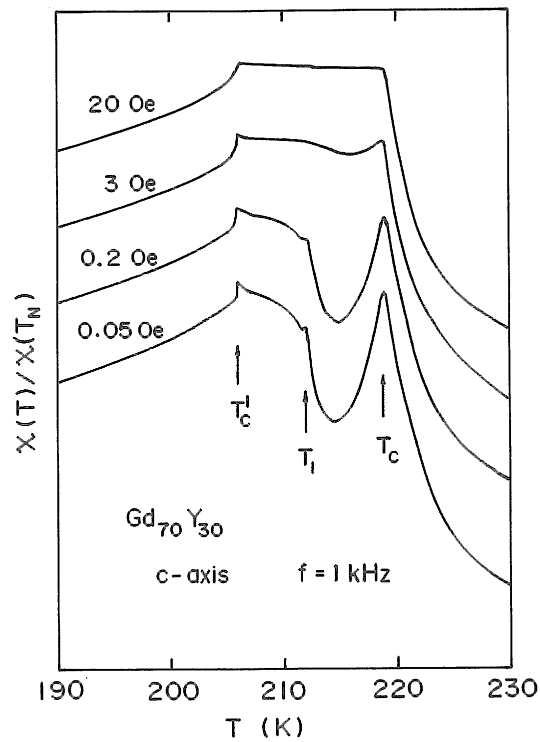

Fig. 4. Low isofield ac susceptibility vs temperature for $Gd_{70}Y_{30}$ along the *c*-axis at various ac magnetic fields.

are followed by an some atomic layers having *c*-axis components down (cones open downwards). The anomalies of the susceptibility curves at T_c, T_1 and T_c^1 show sharp change as decreasing the magnetic field.

§4. Discussion

Using a simplified band model, Kaino and Kasuya[11] have investigated the role of the nonlinear effect of the s-f exchange interaction on the magnetic properties of Gd and its alloys. They pointed out that the nonlinear effect and the easy axis anisotropy stabilizes the antiphase domain structure in infinitesimal s-f exchange. As a matter of fact, the values of $\Delta = I\langle S\rangle/E_f$, where I is the s-f exchange, $\langle S\rangle$ is the expectation value of f spin and E_f is the Fermi energy, vanish at T_c. We conclude that the sharp susceptibility peak at the highest ordering tempeature shows the quasi antiphase domain structure. The magnetic structure is similar to that of Er metal. It is a structure for which several atomic layers having *c* components up (cones open upward) are followed by an equal number of atomic layers having *c*-axis components down (cone open downward) and the basal plane component remains random.

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