Resistivity study of Dy$_{0.93}$Y$_{0.07}$ alloy

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Abstract. The electrical resistivity measurements of the polycrystalline rare earth alloy Dy$_{0.93}$Y$_{0.07}$ in the temperature range 2-300K at different magnetic fields are carried out. Two transitions from paramagnetic (PM) to spiral antiferromagnetic (S-AFM) and S-AFM to ferromagnetic (FM) states are clearly seen in the zero field resistivity data. The various contributions to the electrical resistivity of Dy and Dy$_{0.93}$Y$_{0.07}$ in three different magnetic states are studied. In the ferromagnetic region, the spin wave excitation energy term increases on decreasing the temperature due the enhanced magnetic anisotropy at lower temperatures.

1. Introduction
The rare earth element Dysprosium shows interesting magnetic properties with change in temperature and magnetic field. It is paramagnetic (PM) at room temperature. On reducing the temperature, it undergoes a transition from the paramagnetic state to the spiral antiferromagnetic (S-AFM) state at the Neel temperature ($T_N$). On lowering the temperature further, it transforms from the S-AFM state to the ferromagnetic (FM) state at the Curie temperature ($T_C$) [1,2]. The spiral antiferromagnetic arrangement in the temperature range of 180-90 K is formed due to the competition between antiferromagnetic and ferromagnetic exchange interactions. Substituting Dysprosium with Yttrium changes the strength of exchange interactions and magnetoelastic coupling in the Dy lattice [3,4]. As a consequence, both the transition temperatures are affected and shift towards the lower temperature region on adding the Y in Dy.

The electrical resistivity study of rare earth metals is of significant importance due to changing dynamics at magnetic phase transitions. The electrical resistivity is assumed to be a combination of various scattering phenomena in different magnetic states at different temperature regions. The resistivity of Dysprosium is addition of mainly three contributions viz: (i) residual resistivity due to impurities and disorder present in the system, (ii) phonon scattering and (iii) magnon scattering.

\[ \rho (T) = \rho_{\text{res}} + \rho_{\text{mag}}(T) + \rho_{\text{ph}}(T). \]

The resistivity due to impurities and imperfection in the lattice is independent of temperature whereas the scattering of electrons due to phonons is expected to be a linear dependence of temperature at $T > 0.5\theta$, where $\theta$ is the Debye temperature. The magnetic scattering contribution increases with magnetic entropy [5].

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It is interesting to study the electrical resistivity in changing magnetic states of polycrystalline Dy in different temperature regions. This manuscript describes various contributions to the resistivity in the PM, S-AFM and FM regions of Dy and Dy$_{0.93}$Y$_{0.07}$ alloy.

2. Experimental

For preparing the polycrystalline rare earth alloy, Dy$_{0.965}$Y$_{0.035}$, high purity Dy and Y elements having purity 99.9% are taken in stoichiometric amounts and are melted in pure argon atmosphere by arc melting method. Melting is done several times for making the sample homogenous. The spherical ball obtained after melting is cut into a flat piece. X-ray diffraction (XRD) was carried on Bruker D8 Advance Diffractometer (Cu K$_\alpha$ = 1.54 Å) for initial characterization of the sample. A rectangular bar shaped piece was cut for electrical resistivity measurements. Electrical resistivity measurements have been carried out using standard four probe method on the 9T-ACT PPMS system i.e. AC-Transport Physical Property Measurement System from Quantum Design, USA in the temperature range of 2 - 300 K and magnetic field up to 1.5 T.

3. Results and Discussions

Figure 1 shows the XRD pattern obtained at room temperature, the Rietveld refinement fit, Bragg peak positions and the difference between the observed and calculated pattern for Dy$_{0.93}$Y$_{0.07}$. The XRD data confirm the single phase formation of the prepared sample and no impurity phase is detected. Rietveld refinement of the XRD data using Fullprof software confirms the hexagonal structure of the sample having space group P6$_3$/mmc and the lattice parameters are found to be a = b = 3.61Å and c = 5.67Å.

The temperature dependence of electrical resistivity in the temperature range of 2-300 K has been measured at various constant magnetic fields up to 1.5T. For in-field resistivity measurements, magnetic field was applied at 300K and then resistivity was measured during cooling and heating cycles. Figure 2(a) and 2(b) shows the temperature dependence of resistivity of Dy$_{0.93}$Y$_{0.07}$ in zero and 1.5T magnetic field respectively. Pure Dysprosium goes from PM to S-AFM state at the Neel temperature (T$_N$) =180K via second order phase transition and from S-AFM to FM state at the Curie temperature (T$_C$) =90K via a first order phase transition [6,7]. On substituting 7% Y in Dy, transformation from PM to S-AFM state takes place at ~170K, whereas the S-AFM state transforms to FM state at ~56K at zero field. Both the transition temperatures are shifted towards low temperature region due to the changes in exchange interactions and magnetoelastic coupling with the incorporation of non-magnetic Y in Dy lattice. Figure 2(b) shows that the application of magnetic field ~1.5T on Dy$_{0.93}$Y$_{0.07}$ alloy suppresses the hysteresis observed at zero field, indicating a transformation from paramagnetic to ferromagnetic state, overcoming the antiferromagnetic interactions as seen by earlier magnetization measurements in Dy$_{0.965}$Y$_{0.035}$ alloy [3].

![Figure 1. Room temperature XRD pattern of Dy$_{0.93}$Y$_{0.07}$ with Rietveld refinement fit, difference between the observed data and the fit along with Bragg peak positions.](image-url)
The zero field resistivity data of pure Dy and Dy$_{0.93}$Y$_{0.07}$ has been fitted in the different magnetic
states. Figure 3(a) and 3(b) show the fitting of the resistivity data for Dy and Dy$_{0.93}$Y$_{0.07}$ respectively.

We have subtracted the residual resistivity from the temperature dependent resistivity data and fitted
different scattering contributions to $\Delta \rho = \rho(T) - \rho_0$. The resistivity in the paramagnetic state above the
Neel temperature follows a linear T dependence in the temperature range of 300-180K on account of
electron - phonon scattering i.e. $\Delta \rho(T_{300-180K}) \propto T$. Below the Neel temperature, in the spiral
antiferromagnetic state, temperature dependent resistivity fits well to the relation $\Delta \rho = A*T_1.5 + B*T$.
The linear T dependence in this expression corresponds to the electron - phonon scattering whereas the
$T_1.5$ dependence is the spin contribution.

Below the Curie temperature these systems transform to the ferromagnetic state where the major
contribution in the resistivity is by magnetic scattering. Kasuya [8] has shown that such scattering
gives a $T^2$ dependence to the resistivity at low temperatures. Mackintosh [9] considered the role of
spin wave excitations in the resistivity for the anisotropic ferromagnetic materials like Dysprosium and Terbium. At low temperatures the magnetic contribution to the resistivity for anisotropic Dy and Tb is expected to follow a $T^2\exp(-\Delta/ k_B T)$ behaviour, where $\Delta$ is the energy gap, which represents the energy required for exciting the spin wave against the magnetic anisotropy [9]. Lodge et al. [10] also found the $T^2\exp(-\Delta/k_B T)$ fit more satisfactory than simple $T^2$ term for the thin films of Dy samples below 60K. We obtained the best fit of the resistivity data in FM state to the following equation,

$$\Delta \rho = C\text{(T\textsuperscript{2})}\exp(-D/T) + E\text{T\textsuperscript{5}}$$

(1)

where $D = \Delta/ k_B$. $ET^5$ term represents the phonon contribution at low temperatures. We found that the D values vary significantly with temperature, therefore we divided the FM region in three temperature ranges below $T_C$ and fitted equation (1) in these regions. Values of D obtained in different temperature regions for Dy and Dy$_{0.93}$Y$_{0.07}$ are shown in table 1. The large values of D in the lower temperature region indicate the large spin excitation energy required due to higher anisotropy in the lower temperature region. Further, D values for Dy$_{0.93}$Y$_{0.07}$ alloy are also found to be large in comparison to Dy, indicating the large spin excitation energy possibly due to enhanced anisotropy in comparison to Dy.

![Figure 2(a) - Electrical resistivity of Dy$_{0.93}$Y$_{0.07}$ as a function of temperature in zero field. Inset shows the thermal hysteresis across $T_C$ in cooling and heating cycles.](image)

![Figure 2(b) - Electrical resistivity of Dy$_{0.93}$Y$_{0.07}$ as a function of temperature at 1.5T. Inset shows the overlapping of cooling and heating resistivity curves at 1.5T.](image)

**Table 1. Values of D (K) in different temperature regions.**

| Sample/ T range | (2 - 20)K | (20 - 40)K | (40 - 70)K |
|-----------------|-----------|-----------|-----------|
| Dy              | 30        | 25        | 0.5       |
| Dy$_{0.93}$Y$_{0.07}$ | 39        | 27        | -         |
Conclusion

The transition temperatures vary significantly with 7% Y substitution in Dy as well as with the application of magnetic field on Dy$_{0.93}$Y$_{0.07}$ alloy. The various contributions to the resistivity in different temperature ranges, corresponding to the different magnetic states in Dy and Dy$_{0.93}$Y$_{0.07}$ alloy have been fitted. A $T^2 \exp(-\Delta/k_B T)$ behaviour fits well in the ferromagnetic state, indicating the presence of energy gap corresponding to the energy required to excite the spins against the anisotropy of Dy and Dy$_{0.93}$Y$_{0.07}$ alloy. The larger values of energy gap in the low temperature range and with Y substitution in Dy are noticed on account of higher anisotropy.

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