Low temperature studies of resistivity and magnetoresistivity in Al/Co/Al/Cr/Al films

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ABSTRACT

A set of films, Al/Co(d)/Al/Cr(d)/Al where d = 5nm, 10nm, 15nm, 20nm have been deposited at room temperature under high vacuum conditions. They were investigated for resistivity in the temperature range from 30K to 300K and room temperature magnetoresistivity. The residual resistance ratio (RRR), temperature coefficient of resistance (TCR) and activation energy for dc conduction have been determined. From the magnetoresistivity, percentage of magnetoresistance (MR%) has been determined. At a temperature of 300K and field of 7.5 kG, maximum of 0.025 MR% has been observed in a film. Power laws, for the resistivity-temperature behaviour has been empirically established. It is for the first time that a set of sandwich films in the present configurations have been explored for resistivity at low temperature and magnetoresistivity at room temperature.

Key words: Thin film, multilayers, magnetoresistivity.

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INTRODUCTION

The study of electrical properties of single and multilayers/sandwiches of magnetic metals has always been a subject of great interest to many physicists from the points of view of both fundamental physics associated with the electron transport and their variety of scientific and technological applications. Electrical conductivity in the samples having dimensions comparable to the electron mean free path has also been of interest for many years. The films consisting of ferromagnetic layers with antiferromagnetic coupling such as Fe/Cr, Co/Cr, Co/Ru and Cu/Co have been investigated for transport properties1-3.

It is well known that in ferromagnetic metals there is an additional contribution to the electrical resistivity which is closely associated with the magnetic structure of these metals. This resistivity, $\rho_{\text{mag}}$ is called the spin disorder resistivity4. The low temperature resistivity measurements below 10K in Fe, Co, and Ni revealed $T^2$ behaviour5. The data also indicated $T^{3.3}$ dependence of resistivity above 10K. In pure iron, a linear relation between the electrical resistance and temperature has been observed in the temperature range between 1 and 4.2K 6. The major contribution to the resistivity at these temperatures was expected to be due to electron magnon scattering. After these pioneering works, many people have experimentally and theoretically investigated the temperature dependence of resistivity in magnetic metals in bulk and films. But no many scientists have studied and analyzed the temperature dependence of resistivity in multilayers/sandwich films. Recently such studies have been done on Fe/Ni multilayers in pristine and heavy ion irradiated states7.
The magnetoresistance (MR) effects have been reported for multilayers, Ni/(Cu or Ag or Au)/Fe and Fe/Ag/Co, where the two different ferromagnetic (FM) layers were separated by a nonmagnetic metal (NM) layer\textsuperscript{8,9}. The studies of MR dependence on magnetic layer thickness and number of bilayers in (NiCo/Cu) multilayers revealed that MR decreases with increase in magnetic layers thickness and number of bilayers. The results were attributed to the increase of cumulative structural imperfections with increase of number bilayers\textsuperscript{10}. Many theoretical views have been proposed for explaining the MR versus field curves investigated for multilayers comprising interleaved and separated configurations by different authors\textsuperscript{11-14}.

From the literature it is clear that no many multilayer/sandwich films consisting of both magnetic and nonmagnetic layers in different configurations have been thoroughly explored for temperature dependence of zero field resistivity and that there is no single universal theory available yet for explaining the magnetoresistance in them. Moreover, there are some reports of giant magnetoresistance effects observed in multilayers of ferromagnetic-nonmagnetic and ferromagnetic and antiferromagnetic metals. Here, we report on the studies of zero field resistivity at low temperature and room temperature magnetoresistivity in a set of sandwich films; [Al(20nm)/Co(d)/Al(20nm)/Cr(d)/Al(20nm)] with d=5nm, 10nm, 15nm and 20nm labeled as AC1, AC2, AC3 and AC4 films.

**EXPERIMENTAL**

The films were deposited at room temperature on to the glass substrates, in a standard Hindhivac coating unit, using the high pure elements procured from M/S Alfa Aesar, USA. The separate electron beam guns were used for evaporating Cobalt (Co) and Chromium (Cr) and resistive thermal heating method was employed for the evaporation of Aluminium (Al). The vacuum of the order of $2 \times 10^{-5}$ Torr were maintained in the coating chamber during the deposition of films. The rate of deposition of the films was about 1.5 Ås\textsuperscript{-1} for all films. Thicknesses of the layers were monitored with the help of quartz crystal digital thickness monitor.

For example, in the case of AC1 film, firstly Al layer of thickness 20 nm was deposited using resistive heating, second Co layer of 5 nm was deposited using electron beam gun, third Al layer of 20nm, fourth Cr layer of 5 nm and lastly Al layer of 20 nm. Similarly, the other films were produced.

The electrical resistance measurements were carried out by following four point method in a closed cycle helium cryostat with a standard Lakeshore temperature controller, in the temperature range from 30 to 300K. Temperature was measured using pt-100 sensor. The constant current of 1mA has been passed through the current leads from a Keithley (Model 2400) Source Meter and the voltage developed across the voltage probing leads was measured using Keithley nanovoltmeter (Model 2182A). An electromagnet producing fields up to 7.5 kOe was used for magnetoresistance measurements. In magnetoresistance (MR) measurements, the current was passed parallel to the plane of the film. This is called current in plane geometry (CIP). In MR measurements, the field was applied parallel to the plane of the film. Data was collected through computer using the advanced version LabView software.

**RESULTS**

The resistivity, $\rho$, of all the films has been determined as per, $\rho=(Rtb)/l$, where $R$ is the sheet resistance, $t$ the thickness, $b$ the breadth and $l$ the distance between the voltage measuring leads on the film. The $\rho$ values thus obtained are in the range of $2 \times 10^{-7}$ to $9 \times 10^{-7}$ (Ωm). The variation of $\bar{n}$ with temperature, $T$ is shown in Figs.1. The Residual Resistivity Ratio (RRR) of the films has been estimated as $\text{RRR}=(R_{300K}/R_{30K})/R_{300K}$ and, they are 0.162, 0.154, 0.149, and 0.163 for AC1, AC2, AC3 and AC4 respectively.

The temperature coefficient of resistance (TCR) has been determined in the temperature range from 80K to 300K as $\text{TCR}=(d\rho/dT)/\rho$ where $\rho$ is the room temperature resistivity. The TCR is in
Fig. 1: Plots of resistivity, $\rho$, versus temperature, $T$

Fig. 2: The plots of $\ln(\sigma)$ versus $(1/T)$. The solid lines drawn are the least square linear fits to the data in the regions I & II

Fig. 3: Plots of resistivity, $\rho$, versus temperature, $T$ for the temperature range from 80K to 300K. The solid lines are the least square linear lines
the order of $10^{-4}(K^{-1})$ for the films and they are recorded in Table 1.

As per the conductivity expression, $\sigma = \sigma_0 \exp(E_a / k_B T)$ the plots of $\ln(\sigma)$ versus $(1/T)$ were sketched and shown in Figs. 2. Here, $E_a$ stand for activation energy for dc conduction. In the figures, for each film, two different regions; (300-200K) labeled as Region I and (50-30K) labeled as Region II of conduction are noted. The $E_a$ for each film has been determined by fitting least square linear lines in both the regions separately and the values thus obtained are tabulated in Table 1.

**DISCUSSION**

The resistivity of the present films is in the range reported for other multilayer systems, but much smaller than the perpendicular resistivity measured in Cu/Cr films. The resistivity increased slowly with increasing temperature. The spin as well as lattice waves get excited as the temperature is increased, which results in the enhanced electron-magnon and electron-phonon scatterings. These are reflected in the increase of total resistivity with increase of temperature in the present films. The RRR values of the films are close to unity suggesting that the

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![Fig. 4: Plots of resistivity, $\rho$, versus $T^n$ for the temperature range from 30 to 80K](image)

- a) $n=2.50$, b) $n=2.15$, c) $n=4$, d) $n=1.20$. The solid lines are the least square linear lines.
mean free path of the electrons is broadly constant with temperature. This also implies that impurity (defects) and/or grain boundary scattering rather than phonon scattering is the dominant mechanism. At all temperatures of interest, the resistivity of films increased continuously with increasing magnetic layers (Co and Cr) thickness. The TCR of the present films are in the range of reported values for other magnetic multilayers Cu/Cr $^{19}$ and Cu/Mn $^{16}$ multilayers. The TCR is not affected by the changes in magnetic layer thickness.

In the ln($\rho$) versus $T$ plots, the two distinct regions of different slopes are evident indicating two different activation energies, which are the characteristics of two different scattering mechanisms. Hence, dc activation energy, $E_a$ for all the films in both the regions has been determined. The $E_a$ for all the films is found to be larger in the high temperature region (region I) by one or two orders of magnitude than in the low temperature region (region II). This could be due to enhanced electron-phonon scattering in region I.

Temperature dependence of resistivity has been considered by dividing the entire temperature range into two intervals that is, $T=30K$ to $80K$ and $T=80K$ to $300K$. The power laws of the type, $\rho (T) = A + B T^m$ has been fit to the data in the temperature range from $80K$ $300K$ (Fig.3) and $\rho (T) = C + D T^n$ in the temperature range $30K$ $80K$ $^{[7]}$ (Fig.4). The best exponent coefficients have been extracted in both the temperature ranges and are shown in Table.1. The exponent $m$ was found to be one in all the films establishing a linear relation between resistivity and temperature in the temperature range $80K$ to $300K$. The coefficients $A$ and $B$ were found to be in the orders of $10^{-10}$ and $10^{-7}$ $\Omega m$. In the temperature range $30K$ to $80K$, the linear relation between resistivity and temperature broke and the exponent values determined in this range of temperature were much above unity. The coefficients $C$ and $D$ were in the orders of $10^{-13}$ and $10^{-7}$ $\Omega m$. In the temperature range above $20K$ or so, the electron-phonon s-d scattering $^{7,20}$ $T^3$ term called Block-Wilson term begins has been said to dominate over the electron-magnon $T^2$ term. In our samples, the exponent is between 2 and 3 for AC1 and AC2 and above 3 for AC3 and below 2 for AC4. The $n$ value of 4 in AC3 indicates smooth interfaces between the grains in each layer in this film which yielded reduced electron-phonon scattering. White and woods observed a $n$ value of 3.3 in bulk Fe and concluded that the interfaces between the grains got smoothened and larger grains have been formed at those temperatures. Srivastava et al $^{7}$ have also observed a $n$ value to be greater than 2 in Fe/Ni multilayers both in pristine and irradiated states. The observed differences between the $n$ values of the present four films in the temperature range from $30K$ to $80K$ also infer that the interfaces between the layers and the magnetic layer thickness also affect the temperature dependence of resistivity in addition to the contributions from electron-phonon-magnon scatterings.

The percentage of magnetoresistance (MR%) has been determined by

$$\text{MR}\% = \frac{\rho_H - \rho_0}{\rho_0} \times 100,$$

where $R_H$ is the resistance in field $H$ and $R_0$ the resistance of the film in zero field. At room temperature $300K$, the change in MR% with applied field, $H$ for all films is shown in Fig. 5. The MR measurements for different temperature could not be performed due to unavailability of facility. In the present films, the MR% decreased with increasing field and increased slowly.

Fig. 5: The plot of MR% versus magnetic field, $B$.
with increasing magnetic layer thickness. The decrease of MR% with increase of field is in agreement with literature on many layered films. A maximum MR% of 0.025 has been observed in AC4 which has magnetic layers thickness of 20nm. No saturation of MR% has been observed even for the fields up to 7.5 kG. The small MR% observed in these films may be due to less number of layers present in the films. If the system is grown into multilayers by having more number of repeats of the present structure the higher MR% may be observed, as most of the GMR exhibited systems have large number of repeats of the layered structure\textsuperscript{21,22}.

**CONCLUSIONS**

A set of sandwich films consisting of the metals Al, Co and Cr with varied Co and Cr thickness have been investigated for zero field resistivity at low temperature and room temperature magneto resistivity. The RRR, TCR, activation energy for dc conduction were determined. The functional relations between resistivity and temperature in each of the film have been established. It was unambiguously confirmed that above 80K the linear relation between resistivity and temperature holds. Below 80K, the power law varies from film to film. However, the resistivity variation with temperature below 80K is explainable within the framework which takes into account of electron-phonon-magnon scatterings. The room temperature magnetoresistance increased on a small scale with increasing magnetic layer thickness and it may be further enhanced by making the system to be the multilayered one.

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