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RESEARCH ARTICLE

LOW TEMPERATURE MAGNETIC AND ELECTRICAL PROPERTIES OF (CO/AL) MULTILAYERS

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ABSTRACT

Magnetic multilayers, (Co(50nm)/Al(10nm))$_n$; n =2 and 5 were deposited at 473K, under high vacuum conditions. X- ray diffraction (GIXRD) studies indicated amorphous nature of the films. Atomic force microscope (AFM) has been employed to study surface structure and grain sizes. The magnetization as a function of field at temperatures 150K, 200K and 300K has been measured using the MPMS SQUID - vibrating sample magnetometer (VSM). From the hysteresis loops, coercive field, saturation magnetization, remanent magnetization and ant ferromagnetic coupling were determined. The existence of ant ferromagnetic interaction between Co layers through Al layer has been established for both the films. The low temperature electrical resistivity in the range from 5 K to 300 K has been measured and found metallic behavior in both the films. This is for the first time that (Co/Al) multilayers were investigated for structural and low temperature magnetic and electrical properties and data analyzed thoroughly.

INTRODUCTION

Study of magnetic interactions between the ferromagnetic (FM) layers in multilayered to discovery number of fascinating phenomena and generated lot of interest in the scientific community from both theoretical and experimental points of view (Hartmann *et al.,* 1999; Volkerts, 2011; Spaldin, 2011). Soft magnetic multilayers small thicknesses have the potential to be useful as magnetic sensors (Dieny, 1992; Parkin, 1992). Structural, magnetic and giant magnetoresistance were studied in Ag-Co multilayers (Angelakeris *et al.,* 2003). Multilayers consisting of ferromagnetic metals and nonmagnetic metals were investigated for structure, magnetic and electrical studies (Hutchings *et al.,* 1999; Srivastava *et al.,* 2004). The role of nonmagnetic spacer in tuning the interlayer exchange coupling (IEC) between two neighboring magnetic layers has been first reported by Grunberg (Partha Pratim Pal and Ranjit Pati, 2008). In some multilayers, chromium (Cr) spacer was used and investigated interface roughness (Kumar Dileep and Gupta Ajay, 2005; Kholin *et al.,* 2006), magnetic and electronic structures (Botana *et al.,* 2008). An anomalous behavior of low temperature resistivity has been observed in the films, Co/M/Co (M = Cr or Cr/Ag or Ag/Cr) (Aliev *et al.,* 1998). Structural and magnetic properties were probed in Fe/Cu multilayers for varied Fe layer thickness (El Khiraouia *et al.,* 2008). Interlayer diffusion of nonmagnetic metals C, Cr, Pt (Ding *et al.,* 2005; Shima *et al.,* 2003), Ag (Xu *et al.,* 2007), Al and Cu into the magnetic layers has been studied (Yan Peng *et al.,* 2007). It is known that the interlayer coupling depends on the thickness of spacer layer (Hirayama *et al.,* 1993). AFM micrographs show that the sputtered films result in a quite smooth Co and Ta films and the Ta buffer layer decreases the surface roughness of Co. The thickness of Co layers affects the magnetic properties, both H_c and M_s, dramatically (Vahaplar *et al.,* 2009). Based on the molecular dynamics simulation, the multilayer system of Co/CoAl/Co was simulated and the corresponding quantitative atomic and structural analyses were performed (Kim *et al.,* 2006). NMR, magnetoresistance, and magnetization studies show that the magnetic behavior of Co/Ag (111) multilayers depends strongly on the nominal thickness of the Co layers, which determines the microstructure of the Co layers (van Alphen and de Jonge 1995).

Here, we report on structural and low temperature magnetic and electrical properties of multilayered films, (Co(50nm)/Al(10nm))$_n$ (where n= 2 and 5 represent number of repeats) labeled as CAC1 and CAC2. For the first time detailed studies of structural and low temperature magnetic and electrical properties of (Co/Al) multilayers of present thickness are reported.

MATERIALS AND METHODS

The (Co/Al) $_n$; n= 2 and 5 films were developed using electron beam gun evaporation method at a temperature of 473K. Sigma

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Aldrich make Co and Al were used here. X- ray diffraction (GIXRD) studies were carried out in Brucker-D8 advance diffractometer with Cu-Kα radiation of 1.5406 Å wavelength. Surface morphology has been investigated by Atomic force microscope (AFM). Magnetic hysteresis studies were carried out in an MPMS SQUID – vibrating sample magnetometer (VSM) at three different temperatures 150K, 200K and 300K. The resistivity measurements were carried out by following a four point method in the temperature range from 5 K to 300K in an Oxford Instrument make instrumentation.

RESULTS AND DISCUSSION

Grazing incidence X-ray diffraction (GIXRD) studies

Fig. 1 Shows the XRD pattern of CAC1 film. No peak is observed in the pattern indicating amorphous nature. Similar pattern was observed for CAC2 film. It is reported that the films deposited by the electron beam evaporation technique below a certain critical layer thickness show amorphous nature (Kharmouche *et al.,* 2004). Present result is in agreement with that reported in (Sharma *et al.,* 2009; Archna Jaiswal *et al.,* 2007).

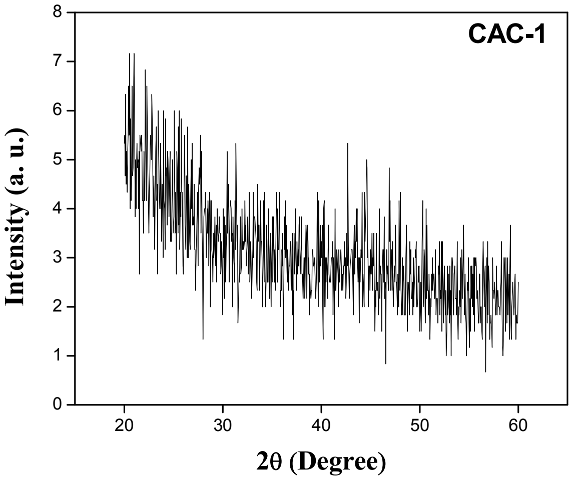


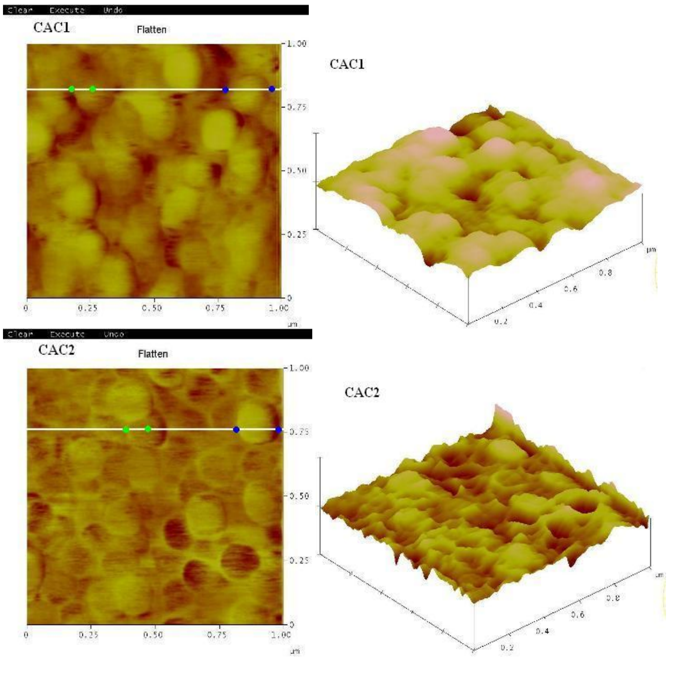
Fig.1. GIXRD spectra for CAC1 film

AFM

AFM images in contact mode with a scan area of 1 μm x 1 μm have been recorded. The AFM images in 2D and 3D for the present films are shown in Fig. 2. The height verses distance profiles were sketched (Sasi and Gopchandran, 2007). And from that, average grain size, D (pair of blue dots) and average surface roughness, h (pair of green dots in Fig. (2a)) were determined. It is noted that D increase and h decease with increase of t (Table 1).

Table 1. AFM parameters of CAC sample

Sample	Surface roughness, h (nm)	Average particle size, D (nm)
CAC1	2.35	247
CAC2	1.40	309



(a) (b)

Fig.2. AFM image of CAC1 and CAC2 films in (a) 2D and (b) 3D

Magnetization

The magnetization, M, as a function of applied field, H, was measured at three different temperatures of 150K, 200K and 300K for the fields applied parallel to the surface of the films. The recorded hysteresis (M-H) loops for the present films are shown in Fig. 3. Both the films exhibited ferromagnetism at these three temperatures. Coercive field, H_c, saturation magnetization, M_s, remanent magnetization, M_r, were determined from the hysteresis loops and they are tabulated in Table 2. H_c is found to be decreasing with increase of temperature. It means that both the films become magnetically softened with temperature (Ying-Ta Shih *et al.,* 2014). Saturation magnetization M_s and remanent magnetization M_r decreased with increasing temperature. The M–H loops are not changed with temperature, which is a typical behavior observed in many soft magnetic materials (Akhilesh K Singh *et al.,* 2013; Herndon *et al.,* 2008; Huang *et al.,* 2001; Brajpuriya, 2010; Ryoichi Nakatani *et al.,* 2004; Li-Feng Liu 2008).

Table 2. Parameters derived from the M-H loops at 150K, 200K and 300K for CAC Samples

Sample	Temperature, K	Coercive field, H_c (T) x10^{-3}	Saturation magnetization, M_s (Am^{-1})	Remanent magnetization, M_r (Am^{-1})	Squareness (Mr/Ms), S	AF coupling (1-S)
CAC1	150	3.089	7.123	2.401	0.337	0.662
	200	2.88	7.129	2.322	0.325	0.674
	300	2.04	7.049	1.862	0.264	0.735
CAC2	150	2.563	12.8	12.183	0.951	0.048
	200	2.562	12.8	12.236	0.955	0.044
	300	2.554	12.675	12.17	0.96	0.039

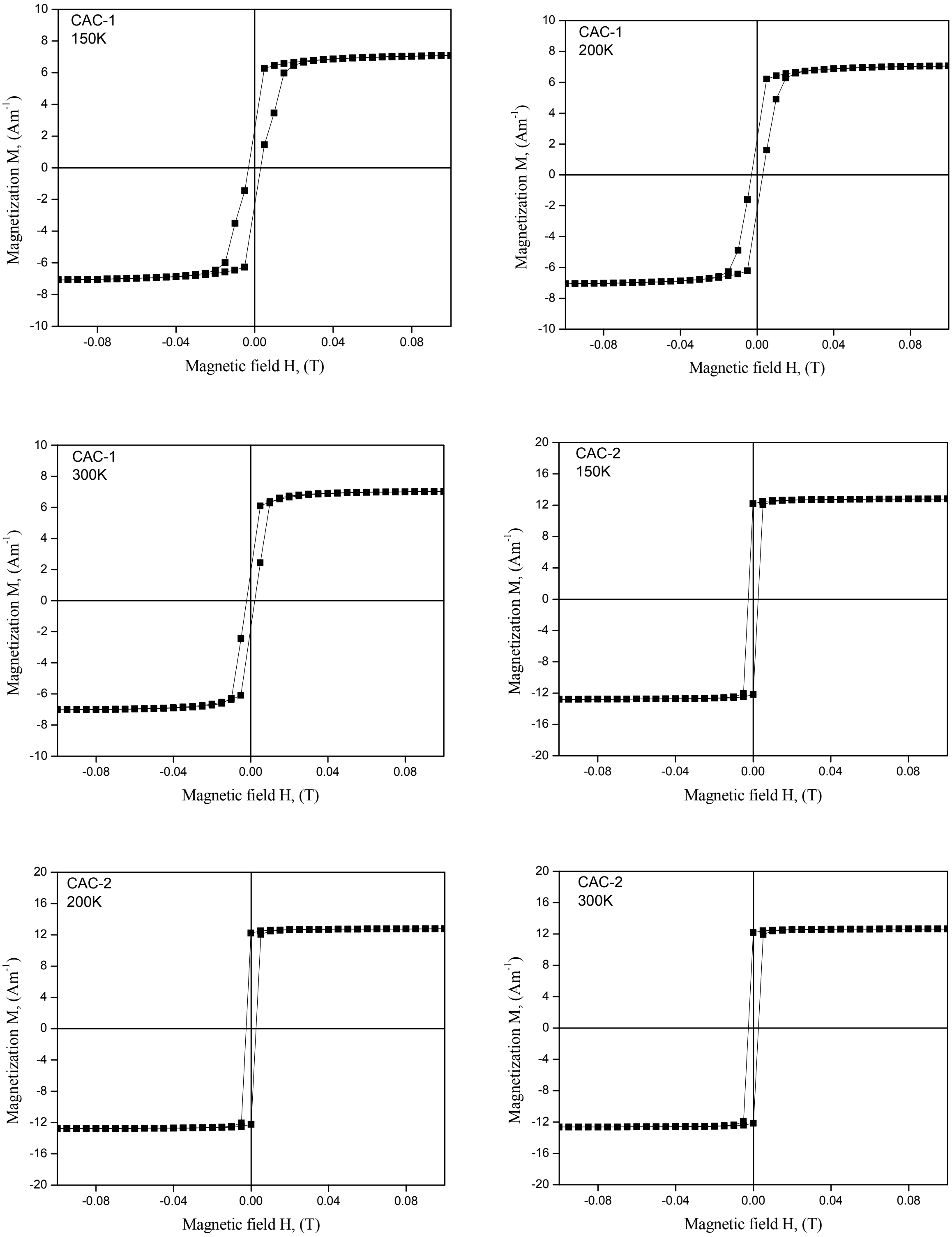


Fig.3. Plots of magnetization versus magnetic field for CAC1 and CAC2 films for different

The size of the saturation magnetization measured in the present films is very small and that is expected for when the films are grown on the glass substrates (Takeuchi *et al.,* 1990).

The finite values of (1-S) obtained for both the films confirm the existence of antiferromagnetic type of interaction between Co layers similar to what has been observed in (Sadashivaiah *et al.,* 2010; Ramanna *et al.,* 2013). Antiferromagnetic coupling is appreciable in CAC1 and somewhat weak in CAC2. The strength of antiferromagnetic coupling decreased in CAC1 and increased in CAC2 with increasing temperature (Parkin *et al.,* 1990).

Resistivity Studies

The measured variation of ρ with temperature for CAC1 is displayed in Fig.4. The resistivity increased with increase of t indicating metallic behavior.

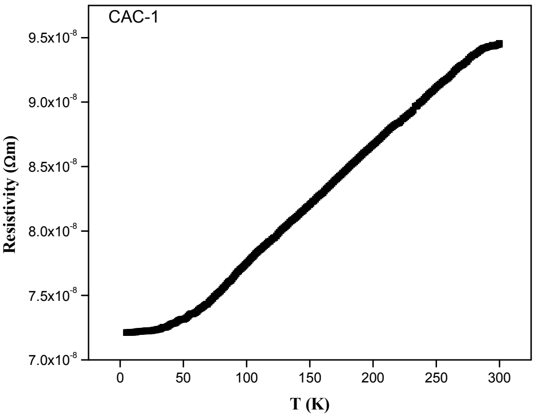


Fig. 4. A plot of resistivity, ρ, versus temperature, T, for CAC1

Similar behavior is observed for CAC2. A careful observation of variation of ρ with T revealed that there exists two different power laws for the measured temperature range as shown in Fig.5 (a-b) for CAC1 and CAC2 films. Hence, the following expressions were fit to the data for different temperature ranges.

$\rho(T) = \rho(0) + a_1 T^k$ for 5K≤ T ≤ 100K

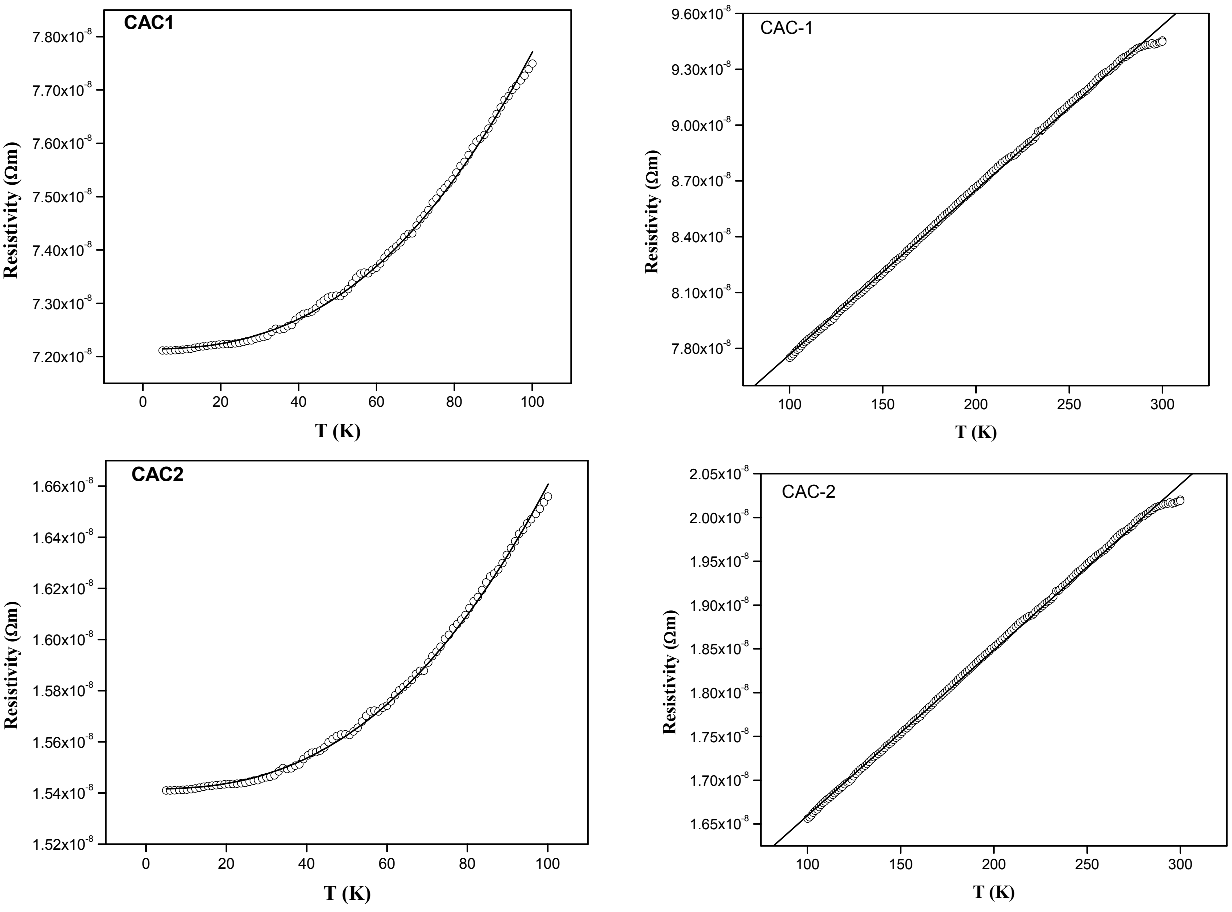
$\rho(T) = A+BT^n$ *for 100K* ≤ T ≤ 300K

Where, *ρ(0)* is the residual resistivity which is taken to be equal to the measured value at 5K in the two films.

By regressional analysis, the coefficient a_1, exponents k, n and constants A and B were extracted. The fit parameters thus obtained are tabulated in Table 3. Both the films produced exponent n to be near unity. For pure nonmagnetic metals, the linearity between resistivity and temperature is expected at high temperature (Taylor *et al.,* 1968).

Table 3. The fit parameters of the CAC films

Sample	ρ (0K) (Ωm) x10⁻⁸	ρ (300K) (Ωm)x10⁻⁸	a1 (ΩmK⁻ᵏ) x 10⁻¹⁴	k	A x 10⁻⁸	B x 10⁻¹¹	n
CAC1	7.211	9.447	5.563	2.5	6.882	8.845	0.999
CAC2	1.54	2.018	1.188	2.5	1.47	1.89	0.999



(a) **(b)**

Fig.5. Plots of resistivity, ρ versus temperature, T for CAC1 and CAC2 film for (a) 5K to 100K and (b) 100K to 300K. The continuous curve passing through the data points are fits to the data

For the present films, in the temperature range, 5K ≤ T ≤ 100K, the exponent, k is found to be 2.5 respectively and that is in agreement with the results on a magnetic layer (Aliev *et al.,* 1998). In this range of temperature, electron-phonon s-d scattering dominates over electron-magnon scattering which is expected to be dominant below 20K (Sadashivaiah *et al.,* 2010). It is concluded that in these films, electron-electron and electron-defect scatterings are predominant below 100K and, electron-phonon and electron-magnon scatterings are predominant above 100K (Ramanna *et al.,* 2013).

Conclusion

(i) The Multilayered films, $(Co(50nm)/Al(10nm))_n$; n = 2 and 5 were deposited. The structure and surface roughness were probed by grazing incidence X-ray diffraction (GIXRD and atomic force microscope (AFM).

(ii) At Three different temperatures of 150K, 200K and 300K magnetic hysteresis loops were recorded in a MPMS SQUID – vibrating sample magnetometer (VSM). At these three temperatures, coercive field, saturation magnetization, remanent magnetization and antiferromagnetic coupling were determined. Antiferromagnetic coupling increased with increase in temperature for CAC1 and decreased with increase in temperature for CAC2.

(iii) Electrical resistivity as a function of temperature in the range from 5K to 300K has been measured by four point method. Both the films exhibited metallic behavior. Relations between resistivity and temperature have been established.

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