Skin depth and Permeability measurements of $Co_{1-x}Sb_x$ alloys

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Abstract - By adding cobalt to CoSb, different $Co_{1-x}Sb_x$ ($0.17 \le x \le 0.44$) alloys have been synthesized to study the ac characteristics of the material. The ac measurements such as permeability and skin depth are calculated using high frequency and dc resistance of samples. It is observed that the permeability of the sample decreases with decreasing frequency of ac input signal and skin depth increases with decreasing frequency of ac input signal. The skin depth is observed to be sensitive to cell parameters. The results are discussed using microscopic as well as macroscopic models.

Index Terms – skin depth, permeability, high frequency, $Co_{1-x}Sb_x$ system

I. INTRODUCTION

The frequency variation of the signal through the substance gives rise to the skin effect. Therefore it is necessary to study ac characteristics of the material along with its dc resistivity. The high frequency resistance R_f of a conductor in a series form is given as equation [1]

$$R_f = R_0[1 + \tfrac{1}{12}a^4 - \tfrac{1}{180}a^8 + \ldots..]\Omega \qquad \text{\_\_\_\_\_\_\_\_ (1)}$$

Where $$a^2 = \frac{2\pi^2 r^2 f \mu}{10^9 \rho} \quad \ldots \text{ for cylindrical conductor,} \qquad \text{\_\_\_\_\_\_\_\_ (2)}$$

R_0 is steady current resistance, r is radius of conductor in cm, ρ is dc specific resistance of conductor material in Ω/cm^3, f is frequency in Hz and μ is permeability of material of conductor.

When frequency is sufficiently high, substantial quantity of current in a conductor is confined to a region very close to the surface. The current density then falls off with depth 'z' from the surface in accordance with the relation[2] (3) z and δ are in the same units and δ is called skin depth [2,3] given by equation (4).

$$\frac{current\ at\ depth\ z}{current\ at\ surface} = e^{-z/\delta} \qquad \text{\_\_\_\_\_\_\_\_(3)}$$

$$\delta = 5033\sqrt{\frac{\rho}{\mu f}} \qquad \text{\_\_\_\_\_\_\_\_\_(4)}$$

II. EXPERIMENTAL

The samples of $Co_{1-x}Sb_x$ were synthesized by first preparing CoSb in induction furnace and annealing. Then cobalt was added to it in appropriate weight proportion and again melted in induction furnace. The samples then were again annealed. To confirm the formation of $Co_{1-x}Sb_x$ samples produced by above mentioned CoSb route [4], XRD patterns were obtained by using the D500 Siemens, Germany and the Rigaku, Japan diffractometers (both use Copper target).

The high frequency resistance is obtained using a simple set up (Fig. 1). The output of a high frequency sine wave generator is applied to a series combination of resistance R of suitable value and the sample of cylindrical shape. The potential drop V_f across the sample is measured with the help of high frequency cathode ray oscilloscope. The high frequency R_f is determined by using the formula,

$$R_f = \frac{V_f \times R}{V_R} \qquad \text{\_\_\_\_\_\_\_\_\_(5)}$$

Similarly a dc resistance R_0 is obtained from the same set up replacing the signal generator by dc power supply.

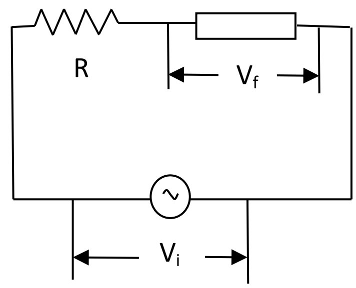

Figure 1: Skin Depth Measurement

III. RESULTS

Permeability and skin depth are calculated using equation (1), (2) and (4) [5]. Thus calculated μ and δ are recorded in a Table 1 and Table 2. The permeability increases nonlinearly with frequency. Assuming the simple relation (6), a graph of $\log(\mu_f - \mu_0)$ Vs log f is plotted in Figure 2 for x= 0.17 which is a straight line with slope m = 1.0006.

$$\mu_f = Af^m + \mu_0 \qquad (6)$$

Table 1: Permeability and Skin depth of System $Co_{1-x}Sb_x$, x = 0.17, 0.20, 0.25, 0.33.

Frequency	X=0.17		X=0.20		X=0.25		X=0.33	
	μ (Ω/cmHz)	δ cm	μ (Ω/cmHz)	δ cm	μ (Ω/cmHz)	δ cm	μ (Ω/cmHz)	δ cm
1MHz	847.81	0.000038	566	0.005421	192.48	0.005254	942.86	0.003344
800KHz	565.9	0.00524	406.65	0.007151	181.23	0.006054	874.08	0.003833
600KHz	441.81	0.006849	252.22	0.01048	147.89	0.007738	633.6	0.005266
400KHz	254.37	0.01105	139.96	0.01723	76.5	0.01317	292.09	0.0095
200KHz	120.49	0.02271	73.39	0.03366	54.43	0.02209	165.63	0.01784
100KHz	85.63	0.0381	60.91	0.05226	31.35	0.04117	57.33	0.04288
80KHz	61.08	0.05044	36.28	0.07571	21.51	0.05557	35.85	0.06063
60KHz	42.41	0.0699	48.38	0.07571	14.64	0.07778	24.97	0.08389

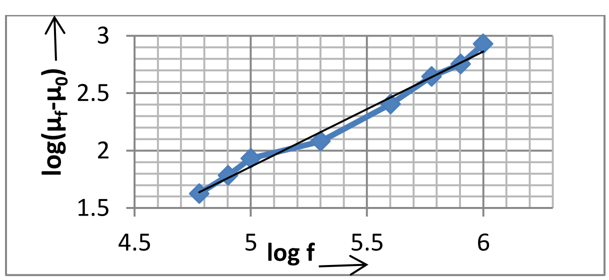

Figure 2: $\log(\mu_f - \mu_0)$ Vs log f corresponding to $Co_{1-x}Sb_x$ with x= 0.17

Table 2: Permeability and Skin depth of System $Co_{1-x}Sb_x$, x = 0.36, 0.40, 0.44.

Frequency	X=0.36		X=0.40		X=0.44	
	μ (Ω/cmHz)	δ cm	μ (Ω/cmHz)	δ cm	μ (Ω/cmHz)	δ cm
1MHz	130.41	0.006447	257.84	0.006708	215.77	0.005648
800KHz	114.13	0.007705	216.17	0.008191	196.8	0.006612
600KHz	81.07	0.01055	173.62	0.01055	143.5	0.008942
400KHz	43.34	0.01768	91.25	0.01783	90.4	0.01379
200KHz	25.32	0.03271	49.8	0.03413	52.38	0.02563

100KHz	11.1	0.06988	22.16	0.07236	23.33	0.05213
80KHz	6.86	0.09938	13.03	0.1055	17.34	0.07045
60KHz	9.15	0.09936	17.38	0.1055	11.61	0.09941

The slopes m corresponding to the remaining $Co_{1-x}Sb_x$ samples are shown in Table (3). These values vary in narrow range and average slope is 1.04. Hence frequency dependence of permeability in $Co_{1-x}Sb_x$ samples is given by

$$\mu_f = Af^{1.04} + \mu_0 \qquad (7)$$

It is interesting to compare variation in the permeability and in the skin depth at a single frequency with antimony concentration x (Fig.3, 4) and the corresponding dc resistivity [6] (Table 3).

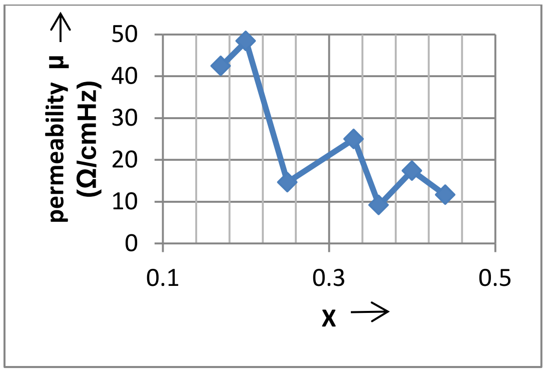

Figure 3: Permeability Vs Antimony concentration X

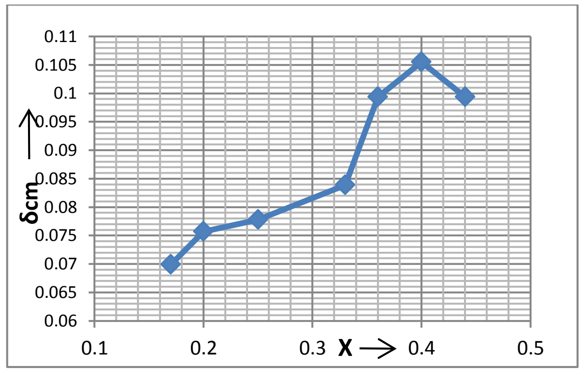

Figure 4: Skin depth Vs Antimony concentration X

Table 3: Permeability, skin depth and dc resistivity of $Co_{1-x}Sb_x$

x	dc Resistivity at Room Temperature 10^{-3} x Ω.cm	Slope m	μ Ω/cmHz at 60 KHz	δ cm at 60 KHz	Particle size A.U.
0.25	0.21	0.895857	15	0.078	5.2
0.36	0.21	1.055316	9	0.099	2
0.44	0.27	1.034111	12	0.099	4.4
0.33	0.42	1.318514	25	0.084	1.5
0.4	0.46	1.072317	17	0.106	4.7
0.17	0.49	1.000683	42	0.07	1.3
0.2	0.66	0.904702	48	0.076	6.1

IV. DISCUSSION

As the composition changes the permeability of these materials may depend upon following factors. 1) The magnetic nature of impurity, 2) distribution and size of clusters of interstitial impurity, 3) defects, 4)density of states of d electrons near Fermi energy.

In these materials excess cobalt acts as the interstitial impurity. Cobalt occupying interstitial as well as lattice sites is magnetic and density of states of d electrons is high and sharply varying near Fermi energy. Hence it may exhibit ferromagnetic behaviour. The systematic change in magnetic moment[4] corresponding to the sample is due to cobalt occupying lattice sites. Hence the unsystematic changes in permeability with composition may be due to formation of ferromagnetic clusters[7] of magnetic and interstitial cobalt, the size and distribution of which is likely to be sensitive to the method of synthesis. It is interesting to note that similar trend is observed in room temperature dc resistivity where the increase in the internal magnetic fields may fluctuate with the size and distribution of ferromagnetic clusters.

Hence the values of permeability, skin depth may give us valuable information about the ferromagnetic clusters and their dependence on the method of synthesis.

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