Effects of thickness and composition on the resistivity of Cu-MgF$_2$ cermet thin film resistors

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Cermet composite thin film resistors of Cu and MgF$_2$ were prepared by conventional vacuum evaporation technique at a pressure of 5×10^{-5} torr and at 302 ± 2 K. The composition by volume was varied from 10 vol % Cu and 90 vol % MgF$_2$ to 100% Cu for thicknesses in the range 110 to 300 nm. Starting materials were co-evaporated from separate molybdenum boats. An empirical formula has been proposed to describe the resistivity-thickness relation for the thin film resistors. The resistivity-thickness relation was found to be of Arrhenius type with ln ρ_f being a linear function of inverse of film thickness in the entire thickness range investigated. A parameter S has been defined to be an estimate of the average separation of the metal islands in the composite thin films. It was observed that S increased with decrease in Cu content of the composite resistors. Another empirical formula has been proposed to describe the resistivity-composition relation for the same film resistors. The relation, obtained by regression analysis of the resistivity-composition data, was found to be exponential in terms of vol % Cu content of the Cu-MgF$_2$ cermets. © *2000 Kluwer Academic Publishers*

1. Introduction

Cermet thin film resistors have been studied because of their potential use in the microelectronics industry [1, 2]. The need for a material which has high sheet resistance, low temperature coefficient of resistance and stability under ambient conditions has motivated investigations into electronic conduction mechanisms in a number of cermet resistor systems such as Cr-SiO [3], Au-glass [4], Mn-MgF$_2$ [5] and Au-SiO$_2$ [6].

In this communication the dependence of electrical resistivity of Cu-MgF$_2$ cermet thin film resistors on thickness and composition is investigated. The investigation not only seeks qualitative effects of thickness and composition but also attempts to quantify them in the form of empirical equations. This thrust is envisaged to avail information on the Cu-MgF$_2$ cermet resistor system for further investigations and possibly future applications. The cermets were prepared by co-evaporation of Cu granules and fine grain MgF$_2$ powder from separate heater sources. The composition of the films resistors was varied from 10 vol % Cu and 90 vol % MgF$_2$ to 100 vol % Cu in the thickness range 110 to 300 nm.

2. Experimental procedure

The resistors were prepared in a coating plant evacuated to $(5 \pm 1) \times 10^{-5}$ torr. Glass substrates used in the investigation were cleaned by conventional technique. Two sizes of substrates were used: large substrates (76 mm × 25 mm) were used for the deposition of resistor tracks and smaller substrates (25 mm × 25 mm) were used in measurement of thicknesses of the resistors.

A set of three masks made by photolithographic technique and etching in H$_2$O$_2$/HCl solution was available. One mask which had six rectangular tracks was used for the deposition of resistor tracks. A second mask was used for the deposition of contact pads onto the resistor tracks. The third mask was used with the smaller substrate such that one half of the substrate was masked in order to create a step in the deposit. The step was later utilised in the determination of film thickness.

The deposition procedure consisted of placing the starting materials in separate boat-shaped molybdenum heater sources. A large substrate and a smaller substrate were then placed in their respective masks mounted centrally 110 mm above the heater sources. An aluminum block heater was placed in thermal contact with the large substrate. A copper-constantan thermocouple sensor was suitably attached to the aluminum block heater to monitor the temperature of the substrate during deposition. The substrate temperature was maintained at 302 ± 2 K. The contents of the heater sources were allowed to outgas before the source shutter was opened. Film deposition was carried out at pre-standardised conditions: source currents of 16 ± 2 A for Cu and 20 ± 2 A for MgF$_2$ for a fixed time. Copper contact pads were subsequently deposited using the same vacuum thermal evaporation technique. The cermet resistors were then removed from the vacuum chamber for immediate measurement of resistance and

for storage in vacuum or in a desiccator. Aluminum was also deposited over the entire surface of the smaller substrate using vacuum thermal evaporation technique. The smaller substrate was used in the determination of film thickness using the Michelson interferometry technique [7].

Direct resistance measurements were made at room temperature and at atmospheric pressure using the Hewlett Packard (HP) digital voltmeter, model 3456A. The 4-point-probe configuration of the voltmeter was used for all resistance measurements [8].

3. Results and discussion
3.1. Resistivity-thickness relation
Fig. 1 shows a typical variation of ln ρ_f against inverse thickness for the Cu-MgF$_2$ cermet films. It is observed that the graphs are approximately linear for film thicknesses in the entire thickness range of about 110 to 300 nm. Damodara Das and Bahulalyan [9] observed a similar trend in Pb$_{0.6}$Sn$_{0.4}$Te thin films. It was observed that the empirical relation describing the resistivity-thickness relation for the thin Cu-MgF$_2$ cermets is of the form comparable to that of Coutts [4]:

$$\rho_f = \rho_o \exp\left(\frac{10S}{t}\right) \qquad (1)$$

where ρ_f is resistivity of the films, ρ_o is limiting resistivity of cermets of large thickness, t is film thickness and S is a measure of the separation of metallic islands embedded in the insulator matrix of the cermets.

From Table I it can also be observed that the Cu island separation, S, obtained from Fig. 1, increased with decrease in Cu content of the cermets. Since S is defined to be a measure of metallic island separation in the cermets it is plausible that one would expect the metallic island separation to increase as the metallic content of the cermets is decreased.

Fig. 2 shows a plot of Cu island separation, S against vol % Cu composition of the cermets using the data shown in Table I. The graph showed that there are three distinct regions of composition with respect to island separation, *viz*.: region I with 10 to 25 vol % Cu content, region II with 25 to 85 vol % Cu, and region III with 85 vol % Cu content. In region I the Cu island separation
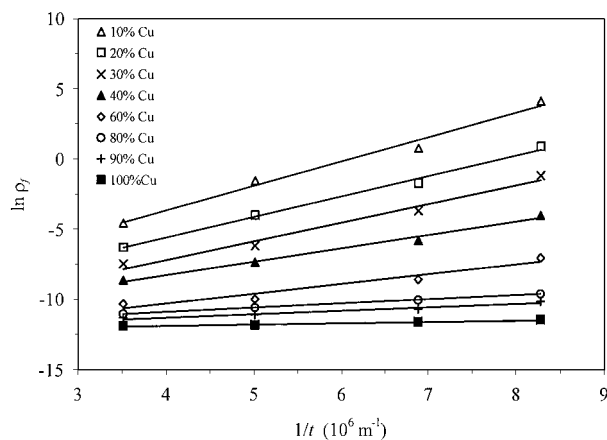

Figure 1 Variation of resistivity with inverse film thickness of the Cu-MgF$_2$ cermets.

TABLE I Variation of the metallic island separation S and ρ_o with metallic content of the cermets

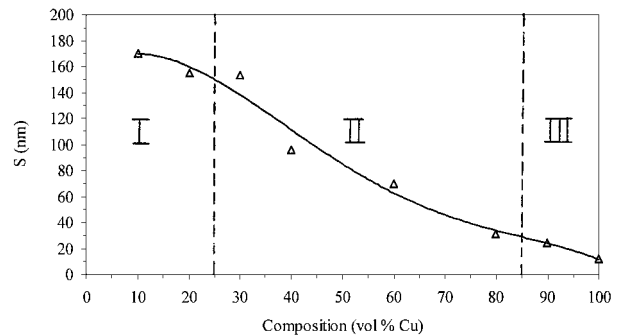| Composition (vol % Cu)	Island separation, S (nm)	Resistivity, ρ_o (10^{-6} Ωm)
10	170 ± 20	45 ± 1
20	155 ± 10	11.2 ± 0.3
30	153 ± 10	2.3 ± 0.2
40	96 ± 6	2.3 ± 0.1
60	70 ± 10	1.4 ± 0.1
80	31 ± 2	7.5 ± 0.1
90	24 ± 4	4.6 ± 0.2
100	12 ± 3	5.6 ± 0.1

Figure 2 Variation of the Cu island separation, S with vol % Cu composition of the Cu-MgF$_2$ cermets.

is large and is not sensitive to vol % Cu content of the cermets, as the separation decreased from 170 to about 150 nm. Cermets falling into region II showed greater sensitivity of island separation to vol % Cu content than those in either region I or III. In fact, the average Cu island separation decreased from approximately 150 to 30 nm in contrast to a drop in island separation from about 170 to 150 nm in region I and from 30 to about 10 nm in region III.

It is interesting to note that Beynon and Olumekor [10] observed similar metallic (Mn) island separation distances in Mn-MgF$_2$ cermets of thickness 25 nm. The Mn island separations were found to be 71.4 ± 19 nm, 42.8 ± 13.9 nm and 33.3 ± 8.5 nm for cermets of compositions 60, 80 and 100 wt. % Mn respectively. The Cu island separations calculated using Equation 1 show a similar trend being 70 ± 10 nm, 31 ± 2 nm and 12 ± 3 nm in Cu-MgF$_2$ cermets of compositions 60, 80 and 100 vol % Cu respectively. Beynon and Olumekor [10] observed further that the Mn islands also decreased with increase in insulator content of the Mn-MgF$_2$ cermets. Although no electron microscopy analysis was carried out on the Cu-MgF$_2$ cermets, the similarities with the observations of Beynon and Olumekor discussed above appear to suggest that the cermets can be grouped into three categories, viz.: dielectric regime (region I), intermediate regime (region II) and metallic regime (region III) whose physical structures, in turn, agree with the observations and descriptions of Abeles *et al*. [11] for Ni-SiO$_2$, Pt-SiO$_2$, Au-Al$_2$O$_3$ and W-Al$_2$O$_3$ films.

3.2. Resistivity-composition relation
The variation of resistivity of the Cu-MgF$_2$ cermets with composition for various thicknesses is shown in
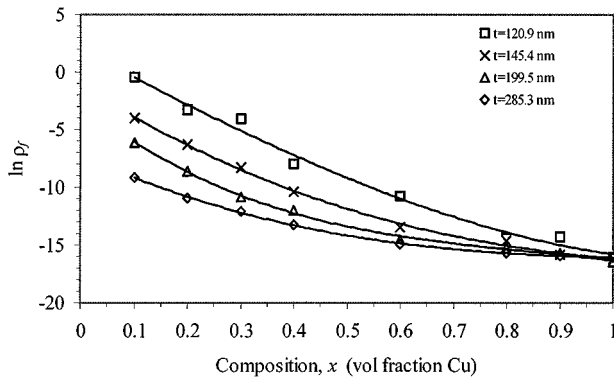
Figure 3 Variation of resistivity with vol fraction Cu content of the Cu-MgF$_2$ cermets.

Fig. 3. It is evident that the $\ln \rho_f$ versus composition graphs were non-linear. The graphs were found to fit into an empirical relation of the form:

$$\rho_f = \rho_c \exp[-(Cx - Dx^2)] \tag{2}$$

where ρ_c is a pre-exponential factor of dimensions Ωm, C and D are constant for a fixed thickness of the cermets but they can vary from thickness to thickness as shown in Table II and x is the fractional metallic content of the cermets.

The variation of C and D with thickness is shown in Table II. Fig. 4 is a graphical representation of how C varies with film thickness. From this graph it can be observed that the magnitude of C varies linearly with film thickness. It can also be concluded from Table II that C is more sensitive to thickness of the cermets than D. The smaller the thickness, the larger is the magnitude of C and the latter corresponds to higher resistivity for the cermets. While the magnitude of C nearly doubled on decreasing the film thickness of the cermets from 285.3 to 120.9 nm, D appeared to remain fairly constant in the same thickness range.

TABLE II Variation of C, D and $\ln \rho_c$ of the empirical resistivity-composition relation with film thickness

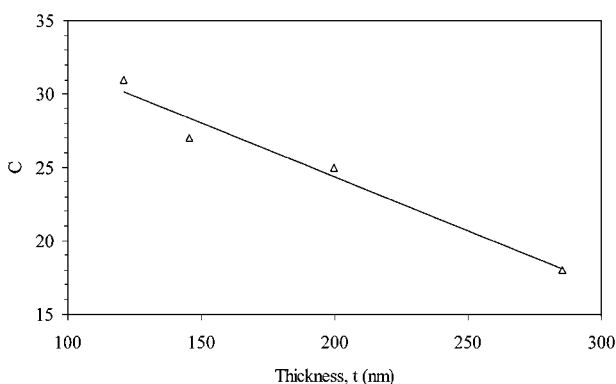| Thickness, t (nm)	C	D	$\ln \rho_c$
120.9	31 ± 4	12 ± 3	2.8 ± 0.8
145.4	27 ± 2	12 ± 1	-1.4 ± 0.3
199.5	25 ± 2	13 ± 2	-4.0 ± 0.4
285.3	18 ± 1	10 ± 1	-7.6 ± 0.1

Figure 4 The variation of C with film thickness of the cermets.

It can be observed in Fig. 3 that all the $\ln \rho_f$ versus x graphs appear to merge at $x = 100$ vol % Cu with a corresponding average resistivity value of 12.4×10^{-6} Ωm. The resistivity value of the thin Cu films at this point is approximately three orders of magnitude higher than the resistivity of bulk pure Cu of 1.7×10^{-8} Ωm at 293 K. Furthermore, the resistivity values, ρ_o, in Table I do not show any particular trend but it is worth to note that all the resistivity values ($\sim 10^{-6}$ Ωm) for all compositions are greater than the resistivity of bulk pure copper. This appears to confirm that thin metal films and cermet films can be used as high resistivity material.

4. Conclusions
An empirical formula has been proposed to describe the resistivity-thickness relation for vacuum deposited cermet thin films in the thickness range of about 110 to 300 nm. A parameter, S was defined as a measure of the metallic island separation in the insulator matrix of the cermets and was used to estimate the variation in Cu island separations in Cu-MgF$_2$ cermets. The magnitude of S increased from 12 ± 3 nm at 100 vol % Cu to 170 ± 20 nm when metallic content of the MgF$_2$ cermets was decreased to 10 vol % Cu for cermets in the 110 to 300 nm thickness range.

Another empirical formula was proposed to describe the resistivity-composition relation for the same vacuum deposited cermet thin films. The relation was of exponential nature as shown in Equation 2.

It was also observed that the limiting resistivity, ρ_o of the cermets of the order of 10^{-6} Ωm was always greater than the resistivity, $\rho = 1.7 \times 10^{-8}$ Ωm of bulk pure copper at 293 K.

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