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Studies on buried layer resistors

G. YADAGIRI, K. K. GOSWAMI
ISRO Satellite Centre, Bangalore, India
K. S. GURUMURTHY
Department of Electronics and Computer Science Engg, UVCE, Bangalore, India
M. SATYAM
Department of Electronics and Communications Engg, IISc., Bangalore, India
K. N. SHANKARA
SCPO, INSAT, ISRO Bangalore, India
E-mail: yadagirig@hotmail.com

Multilayer thick-film technology is one of the important technologies adopted in the miniaturization of electronic systems. Generally, only interconnections are made in the intermediate layers. The possibility of fabricating resistors along with interconnections in the buried layers/intermediate layers using conventional thick-film materials has been examined in this study. The fabrication has been carried out by processing layer after layer. It has been found that the buried layer resistors exhibited a sheet resistivity lower than those fabricated as open resistors. This change in sheet resistivity has been attributed to multiple firings that the resistors undergo during the fabrication. This reduction in sheet resistivity has been found to be due to segregation of active materials. A model has been proposed to explain this change in sheet resistivity through segregation of the active material. The work reported in the paper clearly indicates that buried resistors with consistent values ($\pm$ 10%) can be fabricated using conventional materials. However, the design of the resistors has to be carried out using modified sheet resistivities. The model that is proposed also indicates how one can make a paste that is likely to exhibit the same sheet resistivity for buried resistors and open resistors.
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1. Introduction

As the complexity of electronic systems increases, greater demands are being placed on development of low weight and compact packaging technologies. From this aspect, continuous improvement is made in the multilayer board designs, direct chip-attach technologies, chip-scale packaging technologies, low-temperature cofired ceramic technologies, etc. Multilayer thick-film technology is one of the important technologies adopted in the miniaturization of electronic systems. In this technology, generally, only interconnections are made in all the layers. Usually, the resistors are placed on the topmost layer. Often, the resistors occupy a considerable area of the substrate, limiting the chip/component packaging density. If the resistors can also be fabricated in the buried layers or underlying layers the packaging density can be increased many-fold.

The fabrication of resistors in underlying layers or buried layers needs suitable resistor materials that are stable over multiple firings, compatible with multilayer dielectrics and that allow trimming of the resistors for finer tolerances. There are no suppliers of resistor compositions that can meet the above properties in the commercial market.

Considerable effort is needed for developing resistor compositions specifically for buried layer applications. So a study has been undertaken to find out whether the commercially available compositions/materials can be used for buried layer application. This paper reports the investigations and results of this study.

2. Buried layer resistor

Normally, thick-film resistors are fabricated on Al_2O_3 substrates or on the top layer of the multilayer structures. In this study, the resistors are fabricated on the substrate and the dieletric layers over resistors (Figs. 1 and 2). For this study, industry standard materials are selected from a leading thick film composition supplier (Dupont, P/Ns 5715 conductor, 17 series resistors, 5704 dielectric). Pastes of three types of sheet resistivities, namely 1, 10, and 100 kΩ/sq. are selected for this purpose.

3. Sample preparation

To start with, resistor terminations are printed on the substrate by screen-printing technology using gold composition. Printed terminations are dried and fired.

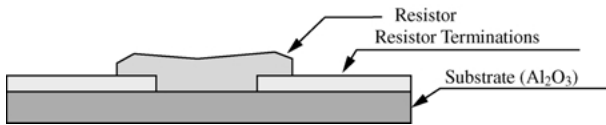

Figure 1 Normal design/fabrication of resistor.

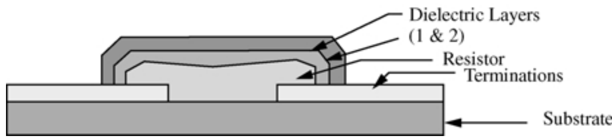

Figure 2 Buried-layer configuration.

Later, resistors are printed, dried, and fired. The resistor values are measured and noted (initial values). Then, two layers of dielectric material are printed, dried, and fired sequentially. All the layers are dried at 150 °C and fired at 850 °C, the temperatures recommended for processing by the paste manufacturer. The resistor values at this stage are found to be different from their initial values.

4. Values of buried layer resistors

The values of buried layer resistors have decreased drastically from their initial values. The change is comparatively lower in resistors that are fabricated using a paste of 1 kΩ/sq. sheet resistivity, and more in resistors fabricated using pastes of 10 and 100 kΩ/sq. sheet resistivity. Tables I, II, and III give the initial and final values of resistors. From the tables it may be seen that resistors fabricated with the paste of 1 kΩ/sq. has come down to 73–86% of its initial value, whereas those fabricated with pastes of 10 and 100 kΩ/sq. have come down to 41–30% and 42–29% of their initial values, respectively.

About 150 resistors on 30 substrates were made and tested for the resistance values. All of them have shown similar behavior.

5. Effect of refiring on resistors with top dielectric

Thick film resistor material/paste is a thixotropic material. The major constituents are the functional material (ruthenium oxide, RuO_2) binder (frit glass), organic vehicle and other volatile materials to make the composition screen-printable on Al_2O_3 substrates. When the printed resistors are dried, most of the volatile materials evaporate and the remaining organic materials are burnt in the preheat zone of the firing furnace. In the sintering zone of the firing furnace the glass melts and binds ruthenium oxide (RuO_2) particles together, which form the conductive/resistive path. Glass, further, helps in binding the resistor film to the substrate.

In this study, resistors formed in the conventional way are refired twice with two dielectric layers above them sequentially to avoid problems connected with pinholes. The second dielectric layer is also found to improve smoothness and enables building of more interconnection layers onto it. During this process, it is found, as mentioned earlier, that the values of the resistances decreased. Hrovat *et al*. [10] studied the micro structural

TABLE I Resistor values for 1000 Ω/sq

Sl. no	Initial value (Ω)	Final value (Ω)	% change
1	233	182	78
2	240	185	77
3	680	506	74
4	706	614	86
5	705	569	80
6	1.18 k	972	82
7	1.52 k	1.32	86
8	1.4 k	1.18 k	84
9	1.54 k	1.2 k	77
10	1.57 k	1.15 k	73
11	1.52 k	1.13 k	74
12	1.9 k	1.65 k	86
13	2.0 k	1.72 k	86
14	2.4 k	2.0 k	83

TABLE II Resistor values for 10 Ω/sq

Sl. no	Initial value (kΩ)	Final value (kΩ)	% change
1	9.8	4.1	41
2	6.28	1.91	30.4
3	13.2	5.4	40
4	14.27	5.34	37.4
5	14.22	5.32	37.4
6	13.52	5.03	37.2
7	14.3	5.29	36.9
8	24.4	9.2	37.7
9	22.8	7.6	33.3
10	21.4	6.6	30.8

TABLE III Resistor values for 100 kΩ/sq

Sl. no.	Initial value (kΩ)	Final value (kΩ)	% change
1	93	39.8	42.7
2	95.2	28.9	30.3
3	106	43	40.5
4	277	98	35.3
5	201.2	50.5	29.3

and electrical characteristics of over-fired thick film resistors. Through their observations from SEM they came to the conclusion that there is a segregation of conducting phase and glass matrix, which is responsible for modified characteristics. On the same lines, the reasons for the decrease in the resistor values are explained using the following model.

6. Model

When the resistors are fired for a second/third time, again the glass melts. The functional material, ruthenium oxide and glass are segregated. Ruthenium oxide, due to its higher density, sinks and gets concentrated at the bottom. The concentration of ruthenium oxide particles at the bottom increases, leading to a film with higher conductivity. The change in sheet resistivity due to this process has been calculated on the following lines.

A cross section of the resistor fabricated in the buried structure is shown in Fig. 3. Fig. 3(a) shows the initial distribution ruthenium oxide (RuO_2) particles, which is

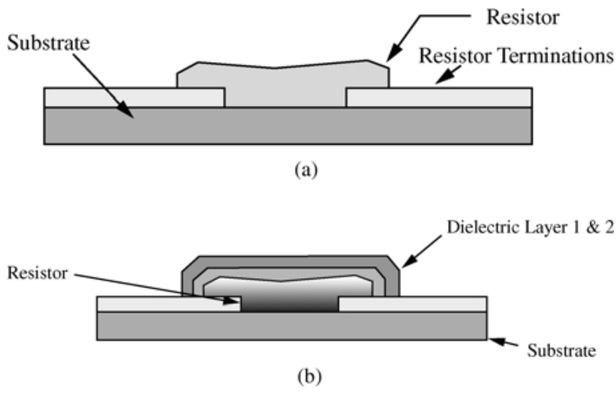

Figure 3 (a) Cross section of the resistor as-fired. The RuO_2 particles are evenly distributed. (b) RuO_2 particles are segregated and settled at the bottom of the resistor due to firing with top dielectric layers.

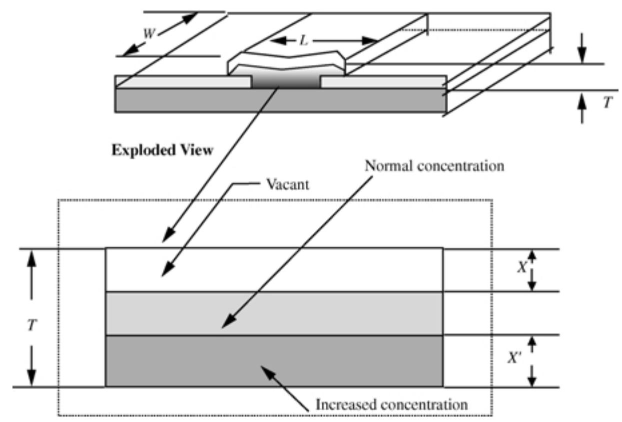

Figure 4 Exploded (cross section) view of the resistor.

assumed to be uniform throughout the thickness of the resistor. The effect of segregation of ruthenium oxide particles after firing with top dielectric layers is shown in Fig. 3(b).

The segregation of ruthenium oxide in glass depends mostly on the terminal velocity (V) of ruthenium oxide particles. The terminal velocity of RuO_2 depends on the relative densities of RuO_2 and glass, the particle size of RuO_2, and the viscosity of the molten glass. The terminal velocity (V) is given by [1, 2]

$$V = 2/9(\rho' - \rho)a^2 g/\mu \quad (1)$$

where ρ' = density of the ruthenium oxide particle
ρ = density of the molten glass
a = radius of the ruthenium oxide particle
g = acceleration due to gravity and
μ = viscosity of the molten glass.

In the process of segregation, all the particles start moving downwards and the distance X travelled by a particle in a time t is given (Fig. 4) by:

$$X = Vt \quad (2)$$

When the top particles move downwards, a layer of glass of thickness X is left behind on the top. This layer X does not contribute to the conduction. On the same lines, one can see that the particles get collected at the bottom resulting in a layer X' with higher concentration. X and X' are functions of t. X' depends on the ultimate concentration, which depends on the way in which the RuO_2 particles are packed in the glass. The conductance of this film depends on X, X' and T (thickness of the resistor). The way in which X' and the consequent change in conductance are arrived at is given below.

The conductances of the bottom layer and the top layer get modified due to the changes in the concentration of the ruthenium oxide particles across the thickness, and these conductance changes are dependent on time. The distance travelled by the particles in time t is given in Equation 2. These particles settle at the bottom with higher packing density. The packed distance X' is given by

$$X' = V't \quad (3)$$

where V' is the velocity with which the bottom layer grows. This depends upon the packing density (concentration) of the particles. Let the concentration of RuO_2 in the bottom layer be C_b. If the concentration of ruthenium oxide in resistors as-fabricated (initially) is C, the rate at which the bottom layer grows V' is given by

$$V' = CV/(C_b - C) \quad (4)$$

Substituting Equation 4 into Equation 3

$$X' = \{C/(C_b - C)\}Vt \quad (5)$$

Let σ_c and σ_{cb} be the conductivities at the RuO_2 concentrations of C and C_b respectively. The conductance (G) at any time t may be written as:

$$G = W/L[\sigma_{cb}X' + \{T - (X + X')\}\sigma_c] \quad (6)$$

Substituting X, X' from Equations 2 and 5 into Equation 6

$$G = W/L[\sigma_{cb}\{C/(C_b - C)\}Vt + \{T - Vt - \{C/(C_b - C)\}Vt\}\sigma_c] \quad (7)$$

where W = width of the resistor; L = length of the resistor; T = thickness of the resistor; t = time; σ_c = conductivity at ruthenium oxide concentration C initially; σ_{cb} = conductivity at ruthenium oxide concentration C_b and V = terminal velocity.

The initial conductance of the film, G_i is written as:

$$G_i = (W/L)\sigma_c T \quad (8)$$

From Equation 8 and Equation 7, G can be written as:

$$G = G_i[1 + \{Vt/(C_b - C)T\}\{(\sigma_{cb}/\sigma_c)C - C_b\}] \quad (9)$$

The normalized conductance equation from the above can be written as:

$$G/G_i = 1 + \{Vt/(C_b - C)T\}\{(\sigma_{cb}/\sigma_c)C - C_b\} \quad (10)$$

7. Terminal velocity

Most often, the particle size (diameter) of the RuO_2 in the resistor composition is around 1 μm. To make calculations simple it is assumed that all the particles are of uniform diameter of 1 μm.

The other data [5–8] from the literature is assumed as follows:

TABLE IV Concentration and conductivity values

Sheet resistivities (SR)		Concentration of RuO_2		Conductivities (1/SR)	
Normal resistivity (k/sq.)	Buried-layer observations (k/sq.)	Normal concentration (%) C	For buried-layer resistors (%) C_b	Normal resistor film conductivity σ	Buried-layer film conductivity σ_{cb}
100	30	11	13.8	1×10^{-5}	0.33×10^{-4}
10	3.0	14	17	1×10^{-4}	0.33×10^{-3}
1	0.8	17.5	18.5	1×10^{-3}	1.25×10^{-3}

$$\rho' = 13.85\,\mathrm{g\,cm^{-3}}$$
$$\rho = 2.85\,\mathrm{g\,cm^{-3}}$$
$$a = 0.5\,\mu\mathrm{m}$$
$$g = 980\,\mathrm{cm^2\,s^{-1}}$$
$$\mu = 10\,\mathrm{poise}$$

The terminal velocity calculated as per Equation 1 is:

$$V = 5.98 \times 10^{-7}\,\mathrm{cm\,s^{-1}} \tag{11}$$

8. Calculation of conductance values

It is observed from the experimental data that the values of resistors reduce when they are fired with a top dielectric layer. The extent of the variation was different for different sheet resistivity materials, as discussed in the previous sections. Studies were conducted by Osamu Abe *et al.* [3] on the effect of concentration of RuO_2 particles on the sheet resistivity of thick film compositions. The values of C and C_b have been obtained (from the graph) corresponding to initial and final sheet resistivities.

The final conductivities and corresponding concentrations for all three sheet resistivities used in the experiments here are given in Table IV. Using these values and the terminal velocity given in Equation 11, the normalized conductances are calculated as a function of time using Equation 10 and are shown in Figs. 5–7. This equation is applicable until complete segregation takes place.

9. Time for complete segregation

It has been mentioned earlier that segregation of RuO_2 and glass takes place when the resistors are fired for a second/third time with dielectric layers covering the resistors. When segregation is complete

$$X'_f = TC/C_b \tag{12}$$

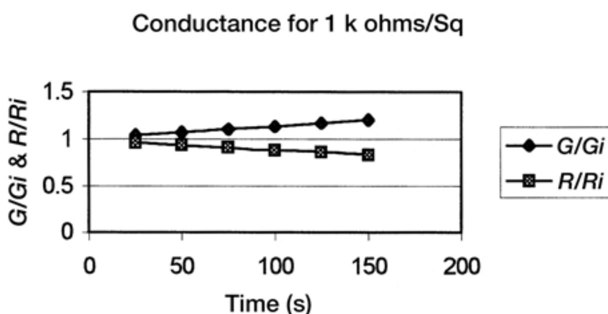

Figure 5 Conductance values for 1 kΩ/sq.

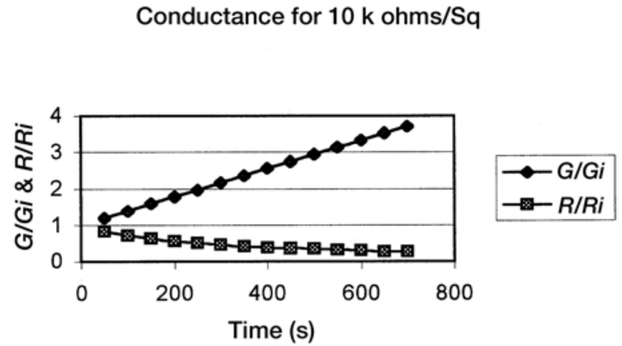

Figure 6 Conductance values for 10 kΩ/sq.

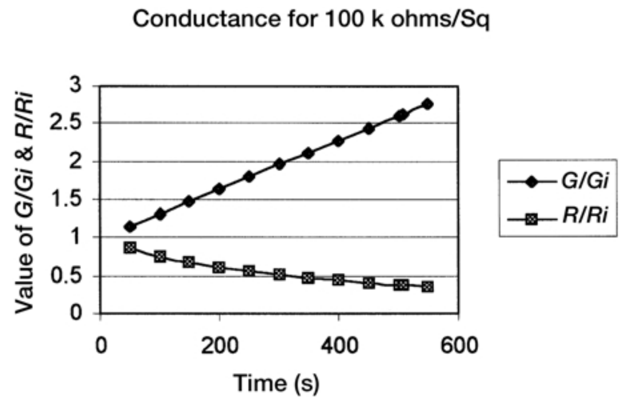

Figure 7 Conductance values for 100 kΩ/sq.

where X'_f is the final thickness of the segregated layer. The time t_s taken for complete segregation is given by

$$t_s = (T - X'_f)/V \tag{13}$$

Substituting the values appropriately, the time t_s taken for complete segregation is calculated for all three sheet resistivities. The time taken for complete segregation in all three sheet resistivities is given in Table V. These segregation times indicate that the segregation is complete in shorter times in the pastes with higher conductivity. This can be understood as the particles have to effectively move shorter distances to the reach the final state.

TABLE V Segregation times

Sl. no.	Sheet resistivity (kΩ/sq.)	Complete segregation time (t_s) (s)
1	1	135
2	10	443
3	100	508

TABLE VI Data on multiple firings

Sheet resistivity (kΩ/sq.)	Buried res. value	Value after 1st refire	Value after 2nd refire	Value after 3rd refire	Value after 4th refire
1	869 Ω	878 Ω	921 Ω	1020 Ω	1010 Ω
	1.17 kΩ	1.17 kΩ	1.22 kΩ	1.35 kΩ	1.34 kΩ
	2.75 kΩ	2.66 kΩ	2.42 kΩ	2.64 kΩ	2.63 kΩ
10	4.1 kΩ	4.4 kΩ	4.6 kΩ	4.3 kΩ	4.7 kΩ
	5.4 kΩ	5.6 kΩ	5.6 kΩ	5.0 kΩ	5.7 kΩ
	9.2 kΩ	8.7 kΩ	7.3 kΩ	5.6 kΩ	6.2 kΩ
100	39.8 kΩ	46.5 kΩ	48.4 kΩ	46.4 kΩ	45.5 kΩ
	43 kΩ	49.6 kΩ	51.7 kΩ	49.5 kΩ	48.4 kΩ
	98 kΩ	114.5 kΩ	119.3 kΩ	114.2 kΩ	112.4 kΩ

10. Effect of multiple firings on buried layer resistors

As explained earlier, the main aim of this study is to understand the behavior of the resistors in the intermediate layers. This means that the resistors are likely to undergo many refirings with subsequent dielectric and interconnection layers. In view of this, the buried layer resistors are subjected to further firing. The values of resistors, after each firing are given in Table VI. It may be observed from the data that the variations of resistor values are very small ($< 10\%$) in subsequent (after dielectric layer firing) firings. The reason for these small variations may be the diffusion of functional material (RuO_2) to the top glass layers thereby decreasing the conductivity of the film. This leads to an increase in the resistance value.

11. Discussion

It is seen from the experimental studies and theoretical modeling that the resistor values decrease drastically when fired with overlying dielectric layers. Further, it is difficult to adjust these values by conventional trimming techniques as they are buried in the intermediate layers. In view of this, the buried layer resistors may be of limited application.

This study gives some insight into the likely factors giving rise to these large variation of resistors so that corrective steps can be taken from the material formulation stage. It was mentioned in the earlier paragraphs that the resistor values decrease due to segregation of RuO_2 and glass. If the process of segregation can be delayed or avoided by making changes in the formulation, the buried resistors can be made stable. By examining the segregation process it may be said that the terminal velocity is the prime contributor to the segregation.

The terminal velocity of the particle is directly proportional to the square of the particle size, inversely proportional to the viscosity of molten glass and proportional to the difference in densities of RuO_2 and glass. Stability of the buried layers can be improved therefore by

1. Using very small particle size RuO_2 powders in the formulation of the resistor compositions.
2. By formulating glass with high molten viscosity and having a density that is close to the density of RuO_2 particles.

12. Trimming of resistors

Thick film resistors as-fabricated have large tolerances (approximately $\pm 15\%$) due to various processing conditions. It is a regular practice to trim these resistors to closer tolerances when required. Normally, lasers or abrasive systems are employed in the trimming process. Both these trimming processes increase the value of the resistor as these methods decrease the width of the resistor.

The buried-layer resistors are covered by the dielectric layers. Both of the above-mentioned methods are not suitable to trim the resistors for finer tolerances.

It is reported in the literature [4] that values of resistors can be adjusted/reduced by localized heating either by applying larger current or by a low-energy laser beam. These methods can be applied to adjust the resistor for finer tolerances. Further experimental studies are being planned in this direction.

13. Conclusion

This study indicates that the sheet resistivity of the buried resistors is lower than the sheet resistivity of the resistors that are not covered. This variation in sheet resistivity has been explained with a model based on segregation of conducting phase from the insulating phase. In addition to this phenomenon, one can expect interfacial modifications at the resistor/substrate interface and resistor/top dielectric interface, which are not taken into account in this model. The type of glass (devitrifying/non-devitrifying) is expected to effect the segregation process and as such the variation in sheet resistivity is expected to depend on the process temperature and the glass that is used. The model described here not only explains the variations in the sheet resistivity in buried layers, but also indicates the way in which pastes can be prepared that result in the same sheet resistivity for buried-layer resistors and open resistors.

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