Size Effect on the Electrical Conduction and Noise of RuO$_2$-based Thick Film Resistors

BI-SHIOU CHIOU, JER-YUAN SHEU, and WEN-FA WU

Department of Electronics Engineering and Institute of Electronics
National Chiao Tung University, Hsinchu, Taiwan

Temperature dependence of sheet resistance for a generic RuO$_2$-based resistor with a composition of 20wt.% RuO$_2$-80wt.% glass (63wt.% PbO-25wt.% B$_2$O$_3$-12wt.% SiO$_2$) is evaluated. A combined tunnel/parallel conduction model is employed to describe the resistivity behavior with respect to the temperature variation. The geometry of the resistive film, such as the aspect ratio and thickness, cast a significant effect on the electrical characteristic of the thick film assembly. It is observed that shorter resistive films exhibit smaller resistivity as compared to that of the longer film. Thinner resistive films have smaller resistivity as compared to the thicker ones. In addition, 1/f noise is the dominating contribution in the thick film resistor. The presence of 1/f noise can be qualitatively explained with the aid of the tunneling mechanism.

Key words: Thick film, resistor, noise

INTRODUCTION

A thick film resistor is a very complicated, non-equilibrium system. It is fabricated by sintering together an intimate mixture of conductive and vitreous nonconductive materials on to a ceramic substrate. The sintered films show a distribution of conducting particles in the insulating glassy matrix. The electrical conduction of the resistor is via these conductive chains. Various models for conduction mechanism have been proposed to describe the electrical properties of thick film resistors. They explain at least qualitatively the electrical behavior of the resistor component.

Typical sintering conditions for thick film resistors range from ~700 to ~1000°C for 10 to 20 min. At these temperatures, interactions among the resistor body, the substrate it is fired on, and the terminations of the resistor occur. Various complicated physio-chemical reactions, such as: dissolution of the substrate ingredients into the glassy matrix of the resistor and metal migration from the screened-and-fired conductor terminations to the resistor. These reactions not only provide the necessary adhesions for the resistor/substrate and resistor/conductor interfaces, but also affect the electrical characteristics of the thick film resistor to some extent depending on the geometry, which includes the aspect ratio and the thickness of the resistive film.

A thick film resistor is a heterogeneous system with conductive chains in an insulating glass matrix. When charges transport through the conductive/insulator interface, the inhomogeneity induces fluctuations of the current, and hence results in noise which decreases inversely with frequency, i.e., the so-called 1/f noise. The presence of noise is troublesome for electrical components, and noise in thick film resistors has been recognized as an important parameter for characterizing thick film materials.

Little work has been done to relate 1/f noise in thick film resistors to a similar type of noise observed in other materials such as semiconductors or metals. Stevens et al. reported that noise was sensitive to the interfacial regions within the conductive phase of the thick-film resistors. De Jeu et al. found that the 1/f noise varied approximately linearly with sheet resistance $R_s$. Aponte et al. reported that for thick film resistors of the same geometry, the magnitude of the noise increases with the resistivity. However, chemical reactions, occurred during the firing of thick film resistors, lead to uncertainty in the composition, and hence the ambiguity in the interpretation of noise measurement.

In this research, the influence of geometry on the electrical conduction and noise of a generic RuO$_2$-based thick film resistor is investigated. A combined tunnel/parallel conduction model is applied to explain the electrical conduction and noise of the material system.

EXPERIMENTAL PROCEDURE

The resistor system selected was RuO$_2$ as conducting phase and glass as a matrix with a composition of 20wt.% RuO$_2$-80wt.% glass. The glass composition employed is 63wt.% PbO-25wt.% B$_2$O$_3$-12wt.% SiO$_2$ which has a density of 4.599 g/cm$^3$. This glass has been extensively studied for the application in thick film microelectronic technology. Powder mixtures of RuO$_2$ (<0.5 um) and glass were blended with ~40vol% screening agent consisting of 10% N-300 ethyl cellulose in butyl carbitol solvent for two hr in a roll mill.

The resistor ink was printed through a 230 mesh stainless steel screen, dried at 120°C for 5 min to remove the solvent, at 350°C for 10 min to decompose the cellulose, and then sintered at 850°C for...
RESULTS AND DISCUSSION

The sheet resistance $R_{\parallel}$ as a function of temperature for the resistor composition 20wt.% RuO$_2$ - 80wt.% glass with various aspect ratios is given in Fig. 1. The sheet resistance decreases rapidly initially, reaches a minimum at temperature range from 400 to 690 K, and then increases as the temperature is further raised. The temperature dependence of the sheet resistance can be explained with a combined tunnel/parallel conduction model proposed by Chiou and Sheu. In this model, the electrical behavior of the interfacial barrier between two neighboring conductive films depends on the thickness of the glass interlayer and the amount of glass infiltrated into RuO$_2$ particle aggregates. At low temperatures, transport through the infiltration layer by tunneling is the predominant process with a temperature dependence of resistance $R(T) = R_{\parallel0} \left(1 + \frac{\Phi}{2kT}\right)$, where $R_{\parallel0}$ is a constant depending on the tunneling barrier; $\Phi$ is the barrier height; $k$ is the Boltzmann's constant; and $T$ is absolute temperature. As the temperature is raised, there are more charge carriers that migrate through the glass interlayer, and an exponential temperature dependence of resistance $R(T) = R_0 e^{E/kT}$ is obtained, where $R_0$ is a constant; and $E$ is the activation energy for charge carrier migration. The temperature dependence of resistance suggests that the electronic characteristic of the interfacial barrier plays an important role in the electrical behavior of thick film resistors.

Also shown in Fig. 1 is that the sheet resistance is larger for resistors with greater aspect ratio. Table I summarizes the parameters for fitting the model for resistors with various aspect ratios. There is a general trend that both $R_{\parallel0}$ and $\Phi$ decreases as the aspect ratio decreases for tunneling through infiltration layer (with the only exception for sample with aspect ratio of 0.35). Further investigation is needed to reveal the correlation between the aspect ratio and other parameters in the conduction model.

The resistivity versus resistor length for the film with various film thickness is given in Fig. 2. The resistivity decreases with decreasing resistor length for resistors with the same thickness as exhibited in Fig. 2. It is argued that the decrease in resistivity is attributed to electrode/resistor interactions which results in the diffusion of the conductive electrode ingredient into the resistor and consequently a drop of resistance near the electrode/resistor interface region. Screen printing produces thickness variations in thick film resistors near and over the conductor overlap regions. In this study, the electrodes were printed on top of the terminations of the resistor, as shown in Fig. 3(a), to eliminate thick-

<table>
<thead>
<tr>
<th>Aspect Ratio</th>
<th>$R_{\parallel0}(k\Omega/\square)$</th>
<th>$\Phi(\mu eV)$</th>
<th>$R_0(k\Omega/\square)$</th>
<th>$E(\mu eV)$</th>
</tr>
</thead>
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<tr>
<td>3.7</td>
<td>5.38</td>
<td>6482</td>
<td>5.60</td>
<td>3055</td>
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<tr>
<td>1.7</td>
<td>5.06</td>
<td>5792</td>
<td>5.27</td>
<td>2605</td>
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<tr>
<td>0.7</td>
<td>3.99</td>
<td>5733</td>
<td>3.50</td>
<td>3145</td>
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<tr>
<td>0.35</td>
<td>3.21</td>
<td>6211</td>
<td>3.36</td>
<td>2875</td>
</tr>
<tr>
<td>0.12</td>
<td>2.80</td>
<td>5200</td>
<td>2.89</td>
<td>2426</td>
</tr>
</tbody>
</table>

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Fig. 1 — Sheet resistance as a function of temperature for resistor with various aspect ratios. Data for sample with aspect ratio of 1.7 obtained from Ref. 5.