High-Voltage Sensitivity Studies of Model Thick-Film Resistors

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Abstract: In this work we seek to better understand the mechanisms governing pulse voltage trimming in disordered conductor-insulator composites. Therefore, we investigate the effect of the composition of thick-film resistors (TFRs) on sensitivity to high voltage pulses. We investigate four series of RuO_2-based TFRs: two different glass compositions and two different RuO_2 grain sizes. For each combination of glass and grain size, different RuO_2 concentrations are studied. It is thought that the grain size influences the sensitivity of a TFR to voltage-trimming, but we show here that the volume fraction of conducting phase relative to its critical concentration is the essential factor governing trimming sensitivity. We also study the effect of the firing temperature on the sensitivity to voltage trimming and show that it decreases with increasing firing temperature.

Key words: Voltage-trimming, Thick film resistors

1. INTRODUCTION

In thick-film technology the production of a resistor with a precise value is very difficult. The variability of a resistor compared to its design value is as large as 20-30% [1], and it usually has to be adjusted in order to fit the requirements for the production of reliable electronic devices. Laser trimming is widely used in industry for this, but has several disadvantages compared to the emerging voltage trimming method. It is difficult to apply laser trimming to very small or burried resistors. In fact laser trimming damages the resistors and therefore makes them less stable, causing a post-trim drift [2]. Voltage trimming, on the other hand makes the resistors less sensitive to voltage pulses and can be applied easily on buried resistors. It was also shown to be reversible [3-4] and allow adjustments to less than 1% for RuO_2-based TFRs [1]. It is also a very cheap trimming method, but has the disadvantage to make the trimmed resistor very sensitive to temperatures and therefore is applicable only on resistors for applications in which the resistors temperature doesn't exceed 100°C [5].

Several models have already been proposed for the physical mechanisms governing voltage-trimming, and a statistical description was proposed by Grimaldi et al. [6], but a complete model is still missing. Most studies about voltage trimming show that this method is applicable for industrial adjustment of resistors, but very few were made about the influence of the composition and microstructure of the TFR on its sensitivity to voltage pulses [7]. Such studies are important because they should allow a better understanding of the phenomena governing pulse voltage trimming.

2. EXPERIMENTAL SETUP

The setup used for the voltage trimming is rather simple. A capacitor is charged to the desired high voltage and then discharged through the resistance being trimmed. Our setup allows charging the capacitor up to 1500 V and its capacity can be changed between 0.1 and 10 nF. The value of the resistance is measured between two voltage pulses or less often as the number of pulses gets high.

The samples studied are disordered conductor-insulator compounds. The glassy particles used as the insulating and bounding matrix have sizes typically of the order of 1-3 µm. Two different glass compositions, called V6 and V2, are studied. The glass transition of the first one takes place at a quite low temperature $T_{V6} = 450°C$ compared to $T_{V2} = 500°C$ for the second one. Therefore the optimal firing temperatures of those two compositions are also different, around 600°C for V6 and 700°C for V2. RuO_2

is used as the conducting phase and for each glass composition, two different conducting grain sizes, 40 and 400 nm and several conducting phase concentrations are studied. For more details about the sample preparation refer to Vionnet-Menot et al. [8] and papers cited therein.

For simplicity we will name the different samples with first the type of glass, then the size of conducting particles and finally the volume fraction of RuO_2. So for example the sample called V6-400-0.11 is composed of 11% of RuO_2 particles having a diameter of 40 nm and the V6 glass as insulating matrix.

3. EXPERIMENTAL RESULTS

In this study we decided to set the same trim voltage and capacity for all measurements. We used respectively 500 V and 0.33 nF, and the trimmed resistors have a length of 0.8 mm, which gives an electrical field of 625 V/mm. Typical trimming results are shown in Fig. 1 where the resistance R of the sample relative to its resistance before trimming R_0 is shown as a function of the number of pulses applied to the sample. The first pulses usually lead to important changes in the resistivity of the sample, which then tends toward an asymptotic final value R_F. We can already see from this figure that the conducting phase volume fraction has a strong influence on the sensitivity of the resistors to voltage trimming and that the most sensitive samples can be trimmed an order of magnitude down as shown by the results on V6-40-0.064.

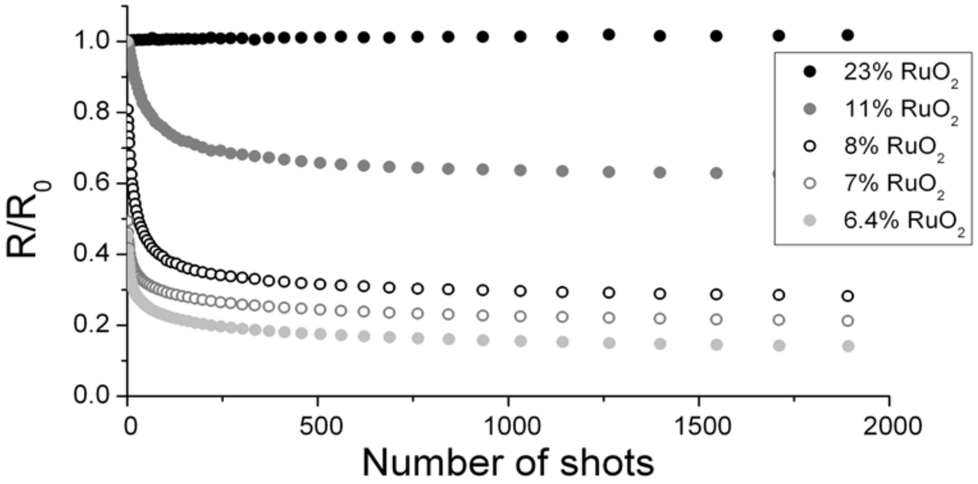

Fig. 1. Trimming results for samples with V6 glass, 40 nm RuO_2 particles and for different volume fractions, fired at 625°C.

In the left panel of Fig. 2 the asymptotic relative change of the resistance (R_F/R_0) is shown as a function of the RuO_2 volume fraction for the two glasses and RuO_2 particle sizes. If we define the sensitivity to trimming as:

$$TS = 1 - R_F / R_0 \quad (1)$$

one can notice that for the V6 glass the TS is monotically increasing as the volume fraction of the conducting phase is diminished. For the V2 glass the situation is less simple with a maximal TS for around 7% of RuO_2 volume concentration. This sensitivity stays constant for lower volume fractions in the case of 400 nm RuO_2 grain size and even diminishes in the case of 40 nm grains. Tobita et al. had observed [1, 7] that the sensitivity to trimming was greater for larger conducting particles. This tendency is also observed here though it seems that the most important parameter governing this sensitivity is the volume fraction of the conducting phase.

At least for the V6 glass there seems to be a critical behavior of the TS as a certain critical RuO_2 volume fraction X_C is attained. The first intuition is of course that X_C is the same critical concentration at which the conductor-insulator transition takes place. We calculated this critical concentration from resistance measurements for 8 different volume fractions for both RuO_2 particle sizes. We found:

$$X_C = 5.3 \pm 0.2\% \qquad \textit{for V6-40}$$

$$X_C = 6.1 \pm 0.1\% \qquad \textit{for V6-400}$$

These critical concentrations were calculated from the V6 samples, because their caracteristics are more stable and better controlled than those of V2 samples.

If we now look at the resistance change (R_F/R_0) as a function of relative distance to X_C, we see that for the glass V6, the difference between the samples with 40 nm and those with 400 nm conducting particles has almost completely disappeared. It seems that both compositions have the same sensitivity to trimming for a same distance to the critical concentration. Again for the V2 glass the situation is less clear, mostly close to the percolation threshold, but as said above, this composition is anyway less well-behaved. This result indicates that the sensitivity to trimming is mostly governed by the topology of the composite material rather than by the details of its composition such as the grain size. For higher RuO_2 volume fractions there are more parralel routes carrying the current and the changes due to the trimming at the grain boundaries have a lower impact on the total resistance of the sample.

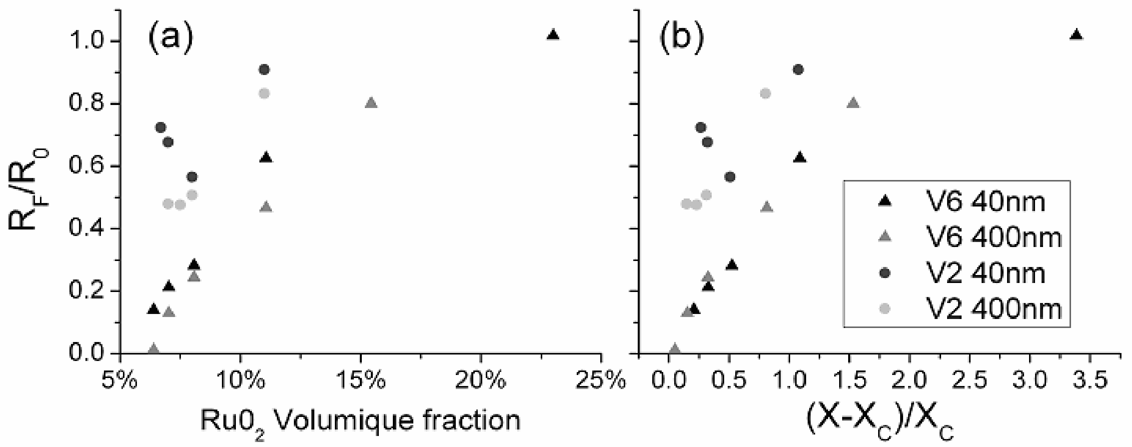

Fig. 2. The ratio between the initial and the final resistance after trimming of the sample as a function of: (a) the conductive phase volume concentration, (b) the relative difference between the RuO_2 volume fraction X and its critical volume fraction X_c. The V6 samples were fired at 625°C and the V2 at 700°C.

It was proposed by Feldbaumer et al. [3] that the resistance changes only if the temperature during voltage trimming exceeds the maximum temperature reached during the firing process. As a verification of this assumption, we study in Fig. 3 the influence of the firing temperature on the TS. As seen in panel (b), the TS decreases as the firing temperature is increased and becomes almost zero for the highest temperatures studied here ($R_F/R_0 = 0.96$ for $T_F = 675°C$). As we can see from panel (a) of this figure, the resistance of the samples has a maximum around $T_F = 600°C$ and decreases for higher and lower temperatures. Therefore the change in TS cannot be only attributed to the change of the resistance with firing temperature which supports the assumption made above.

4. CONCLUSION

The study of model pastes allowed us to study the influence of several parameters on the sensitivity to trimming (TS). We found that the firing temperature (T_F) has a rather strong impact on the TS, which monotically decreases with increasing T_F. This result supports the idea that trimming is efficient only if the temperature of the sample during trimming exceeds the maximal temperature reached during the firing of the paste. Our results also confirmed that for a same volume fraction, the size of the conducting grains had an impact on the TS: compounds with larger conducting grains are more sensitive to voltage trimming. A more intersting result is that this difference disapears if we compare samples with a same relative difference to the critical volume fraction (X/X_C-1), rather than with the same volume fraction X.

This is an interesting finding because it suggests that it is not the grain size or detailed structure of the sample that is important for the TS, but the underlying topology of the current carrying network. To our knwoledge this is a new result, which shows that the theoretical description of voltage trimming has to take the topology of the conducting network into account. Therefore, it seems usefull to further investigate the random resistor network model proposed for voltage trimming [6].

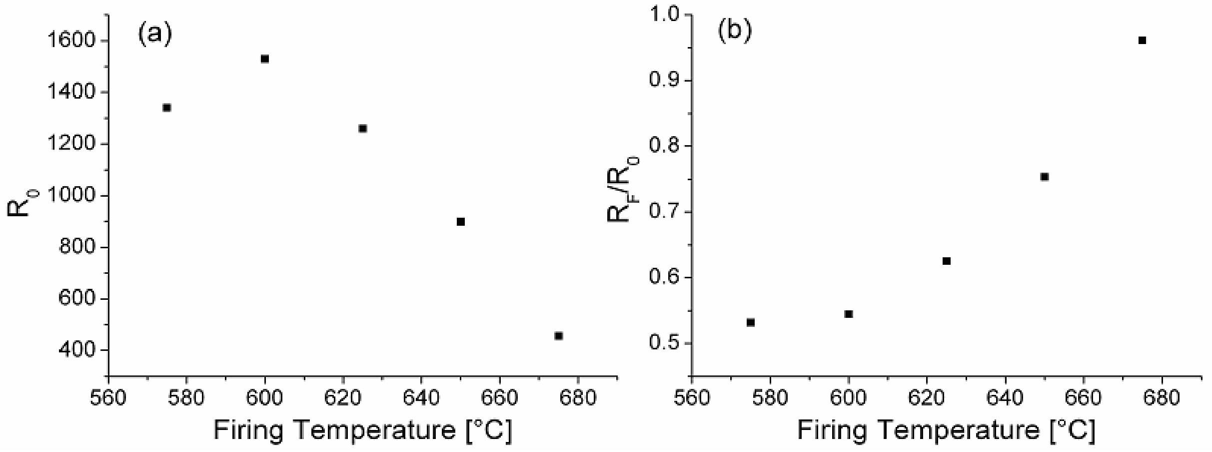

Fig. 3. Resistance (a) and sensitivity to trimming (b) vs. the firing temperature for V6-40-0.11.

5. REFERENCES

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