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Effects of High Voltage Pulse Trimming on Structural Properties of Thick-Film Resistors

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Abstract:
Nowadays, compact and reliable electronic devices including up-to-date ceramic micro-electro-mechanical systems require thick-film resistors with significantly reduced dimensions and stable and precise resistance values. For that reason, instead of standard laser trimming method, high voltage pulse trimming of thick-film resistors is being introduced. This method allows controlled and reliable resistance adjustment regardless of resistor position or dimensions and without the presence of cuts. However, it causes irreversible structural changes in the pseudorandom network formed during sintering causing the changes in conducting mechanisms. In this paper results of the experimental investigation of high voltage pulse trimming of thick-film resistors are presented. Obtained results are analyzed and correlations between resistance and low-frequency noise changes and changes in conducting mechanisms in resistors due to high voltage pulse trimming are observed. Sources of measured fluctuations are identified and it is shown that this type of trimming is a valid alternative trimming method to the dominant laser trimming.
Keywords: *Thick-film resistors, High voltage pulse trimming, Random resistor network, Structural properties, conducting mechanisms, low-frequency noise.*

1. Introduction

Thick film resistors have been used for decades but due to their reliable performances they are still commonly used in both commercial and specialized electronics. For years they have been used in sensitive telecommunications equipment and various sensing applications. However, when micro-electro-mechanical systems (MEMS) technology emerged, thick-film technology became useful alternative for micro-machining silicon. The most MEMS are made of micro-machining silicon combining electrical and mechanical components. Such micro system might comprise one or more sensors and actuators and adequate electronic circuitry to condition the sensor signal and generate an electrical signal for actuator. Nowadays, some MEMS applications require ceramic materials in combination with thick-film technology. The fact that thick-film technology can be used not only to produce the sensor and actuator elements, but to form electronic circuits for signal processing makes room for this technology in fast-growing MEMS market. The continuous trend towards smaller, faster and cheaper devices lead to increased complexity of thick-film devices and significant reduction of resistor dimensions. Therefore stability and precise resistance values are of the great importance. Laser trimming, that was dominant trimming method of thick-film resistors, cannot meet the new requirements. Extensive research of high-voltage pulse stressing of thick-film resistors [1-6] resulted in an alternative trimming method [7]. High voltage pulse trimming could

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provide controllable resistance changes without the presence of cuts regardless of resistor dimensions or position. This paper investigates effects of high voltage pulse trimming on structural properties of thick- film resistors from the aspect of random resistor network model. Applied voltage pulses cause structural changes in the complex network formed during sintering and our goal is to investigate nature of these changes using resistance and low-frequency noise measurements. Experiment – test sample fabrication and trimming method are described in section 2, and experimental results and discussion are given in section 3.

Test sample fabrication high voltage pulse trimming

Behavioral analysis of high voltage pulse trimmed thick-film resistors was performed using thick-film test resistors shown in Fig. 1. Test resistors, 3 mm long and 1mm wide, were formed on ceramic alumina (96 % Al_2O_3) substrates using conventional screen-printing techniques. Resistors were realized using commercially available resistor composition with sheet resistance of 10 kΩ/sq in combination with PdAg conductor composition. After screen printing process, all of the wet layers were leveled for 15 min at the room temperature, dried at the infrared conveyer drier in 10 min-150 ºC cycle achieving 25±3 μm thickness of resistive layers. Conductive layer was sintered using 30min cycle and resistive layers were sintered using 60 min cycle with peak temperature of 850 ºC for 10 min (Fig. 2).

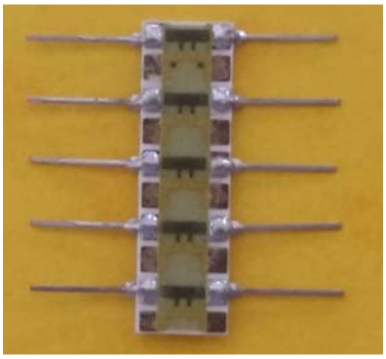

Fig. 1. Thick-film test resistors trimmed by high voltage pulses (resistor width w = 1mm, resistor legth l=3 mm, sheet resistance Rsq = 10 kΩ/sq).

In order to analyze the effects of high voltage pulse trimming Haefely P6T impulse generator was used. Resistance measurements were performed using HP34401A instrument. Quan-Tech Resistor Test Set, Model 315B was used for noise index measurements at 1 kHz. Voltage noise spectrum was measured using nanovolt amplifier Mod. 103A, Kithley and HP-3561B Dynamic Signal Analyzer in the frequency range of 10 Hz to 10 kHz. All measurements were performed at room temperature (T = 295 K).

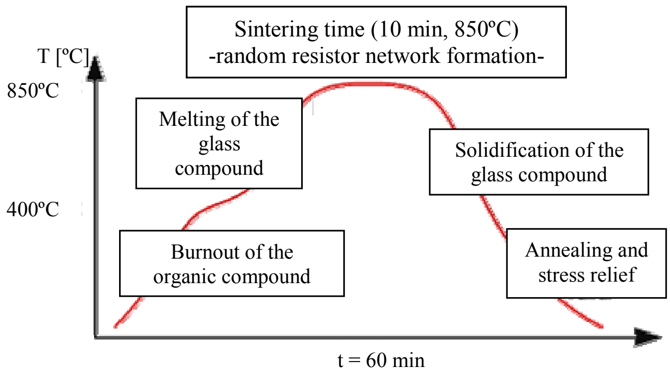

Fig. 2. Time-temperature profile for thick-film resistors used in the experiment.

Experiment consisted of two sets of measurements. During the first test thick-film resistors were subjected to a multiple series of 10 pulses with increasing amplitudes from the 0.5 kV to 3.75 kV range with 125 V step. The second test consisted of multiple series of 10 pulses with 3 kV amplitude. Experimental conditions were selected in such a manner that resistance values gradually changed without the possibility of catastrophic failures. Resistance, noise index and current noise spectrum were measured. Quality of thick-film resistors is usually characterized by the resistance drift and the change in noise index values. However, the information stored in low-frequency noise spectroscopy helped us identify sources that generate measured fluctuations caused by trimming.

2. Experimental results and discussion

The results of our experiments obtained by resistance and noise index measurements for 10 kΩ/sq resistors trimmed by energy of high voltage pulses are given in Figs. 3 and 4. Mean values of the experimental results showed that during trimming using multiple series of 10 high-voltage pulses with increasing pulse amplitude for each series, progressive resistance decrease begun after the impact of ten pulses with 1.75 kV amplitude. After the impact of 10 pulses with 3.125 kV amplitude resistors exhibited more significant resistance change until the maximum of the resistance decrease was reached after the impact of ten pulses with 3.75 kV amplitude. Higher pulse amplitudes were not applicable because they caused different reliability issues resulting in significant resistance increase and with further trimming in resistor failure. Results obtained by noise index measurements showed that noise index increased with resistor trimming reaching maximum value at the point of maximal resistance change.

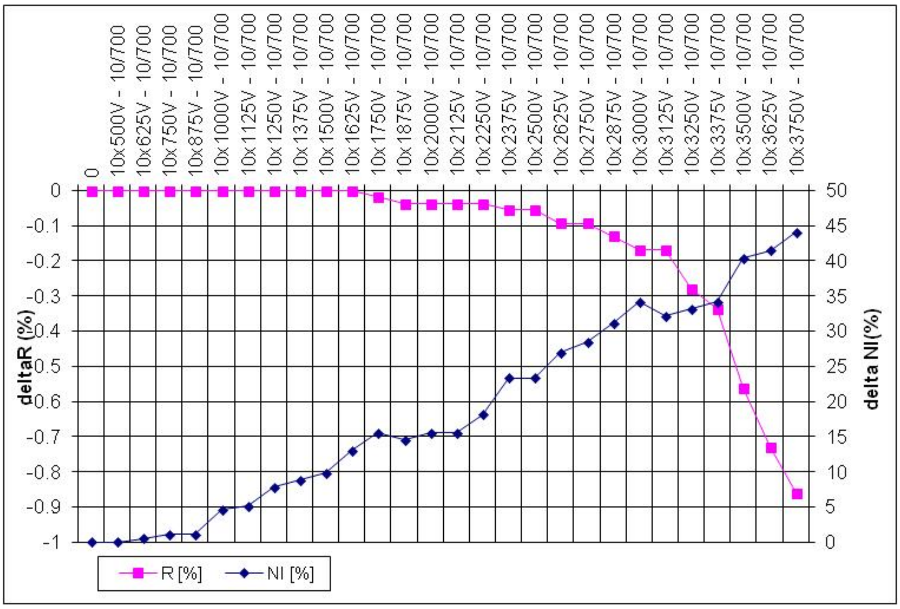

Fig. 3. Experimental results for relative resistance and noise index changes due to resistor trimming by multiple series of 10 high voltage pulses with increasing amplitudes.

During the first part of the experiment the 3 kV pulse amplitude was singled out as the initial point of significant resistance decrease. For that reason, the second part of the experiment that involved resistor trimming by energy of multiple series of 10 pulses with constant 3 kV amplitude, was performed. Obtained experimental results are shown in Fig. 4. It can be seen that resistance progressively decreased until reaching the maximum change and further trimming did not cause further decrease. Measured noise index changes showed significant increase until the maximum of 27 % was reached and, in accordance with resistance behavior, further trimming did not cause further noise index changes.

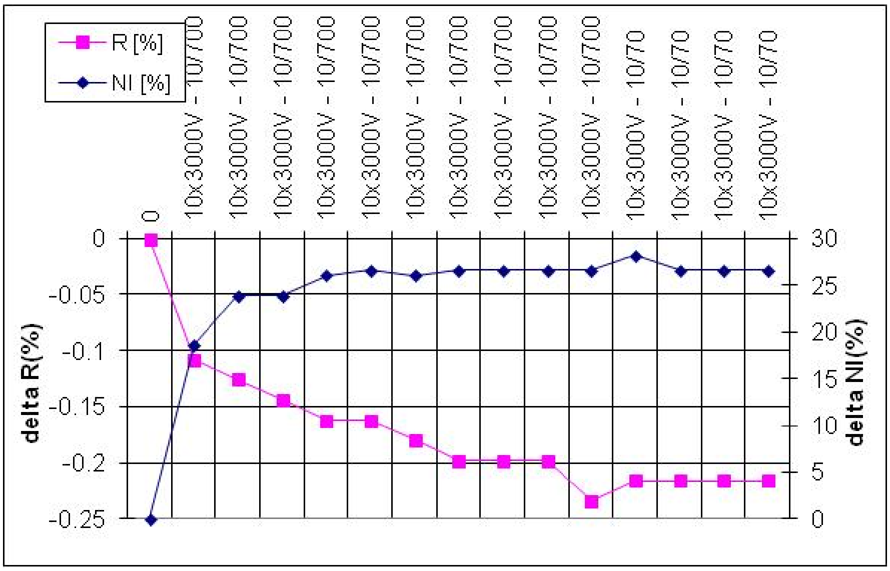

Fig. 4. Experimental results for relative resistance and noise index changes due to resistor trimming by multiple series of 10 high voltage pulses with constant amplitude.

Observed resistance decrease could be explained by microstructural changes in thick-film resistors due to high voltage pulse trimming. Structure of the resistor can be described using random resistor network model [8]. In thick-film resistors charge transport takes place via complex conductive network formed during firing by sintering metal-oxide particles surrounded by glass (Fig. 2.). The sintering process results in random and spatially uneven distribution of conduction and glass phase as can be seen in Fig. 5.

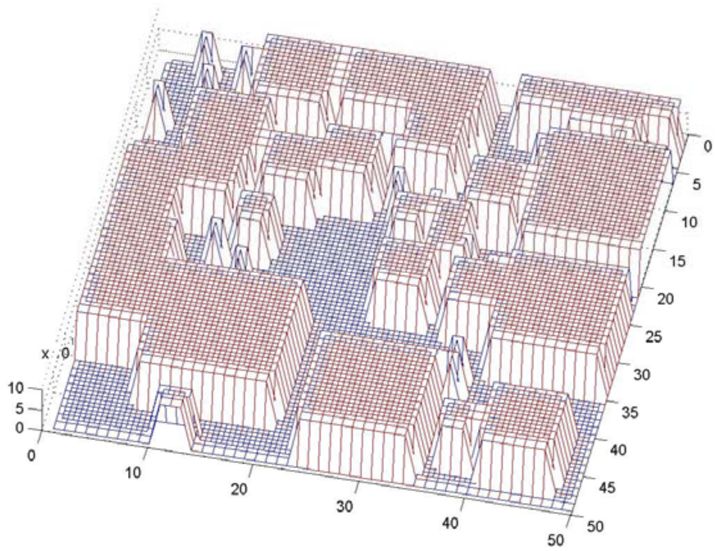

Fig. 5. 50x50 elemental cell based on random resistor network model obtained using computer simulation of thick-film resistor [9] with Rsq = 10 kΩ/sq (low regions–glass particles, peaks–conducting particles).

Random resistor network model, based on deterministic model combined with site percolation model with double percolation, views thick-film resistors as a complex network consisting of insulating areas and several conducting chains in which some particles are in contact and some are separated by thin glass layers thus forming metal-insulator-metal structures. In that case metallic conduction through conducting particles and sintered contacts and tunneling through glass barriers determine the current flow. Due to pseudorandom sintering process, as a consequence of the presence of the impurities and partially dissolved metal-oxide in glass phase, traps are present in insulating layers that contribute to multiple tunneling processes. If we assume that thick-film resistor consists of M parallel conducting chains the total resistance of the resistor can be given as [8]:

$$R = \frac{K_B}{M} R_B + \frac{K_C}{M} R_C, \tag{1}$$

where K_B is the number of barriers and K_C the number of contacts. R_B and R_C are barrier and contact resistances, respectively:

$$R_B = \frac{h^2 s}{q^2 A (2mq\Phi_B)^{1/2}} \exp\left[\left(\frac{32\pi^2 mqs^2 \Phi_B}{h^2} \right)^{1/2} \right], \tag{2}$$

$$R_c = \frac{\rho}{\pi a}, \tag{3}$$

where q and m the absolute electron charge and its effective mass respectively, h Planck's constant, s and Φ_B the potential barrier width and height respectively, $A=\pi a^2$ the barrier cross section and ρ the specific resistance of the contact. The resistance change caused by trimming is a result of change in conducting conditions due to contact and barrier resistance changes. Electrical field inside metal-insulator-metal structure during high voltage pulse trimming is insufficient to induce dielectric breakthrough and cause increase in contacts of particles causing the decrease in total resistance of the resistor. However, trimming affects electrical charges captured within metal-insulator-metal structures and concentration of traps resulting in change of barrier resistance. Also, a non conducting particle chain can make transition to a conducting state thus causing a decrease of the total resistance of the resistor. Having in mind that the low-frequency noise in thick-film resistors [1-3] is the consequence of electrical charge transport fluctuation, results of noise index measurements were in agreement with resistance behavior. From the Fig. 3 we can conclude that high voltage pulse trimming modulates conduction by influencing the potential barrier height of metal-insulator-metal structures. Noise index values exhibited greater sensitivity to these microstructure changes than resistance. Fig. 4 shows that during trimming using high voltage pulses with the same 3 kV amplitude, initial few series of pulses affected conducting mechanisms resulting in resistance and noise index changes.

Established correlation between structural properties and low-frequency noise can also be illustrated using current noise spectra measurements. The normalized current noise spectra before and after trimming by energy of multiple series of 10 high voltage pulses with increasing amplitudes are given in Fig. 6. Total current noise spectrum incorporates contributions of thermal noise, 1/f noise and noise with Lorentzian spectrum. Thermal noise is the only frequency independent contributor.

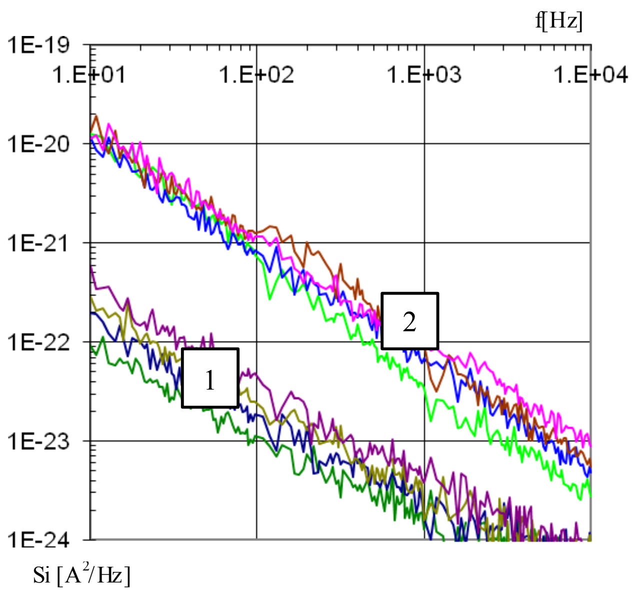

Fig. 6. Experimental results for current noise spectra for thick-film resistors trimmed by the multiple series of 10 high voltage pulses with increasing amplitudes (1- before trimming, 2 - after trimming, full lines - fitting results).

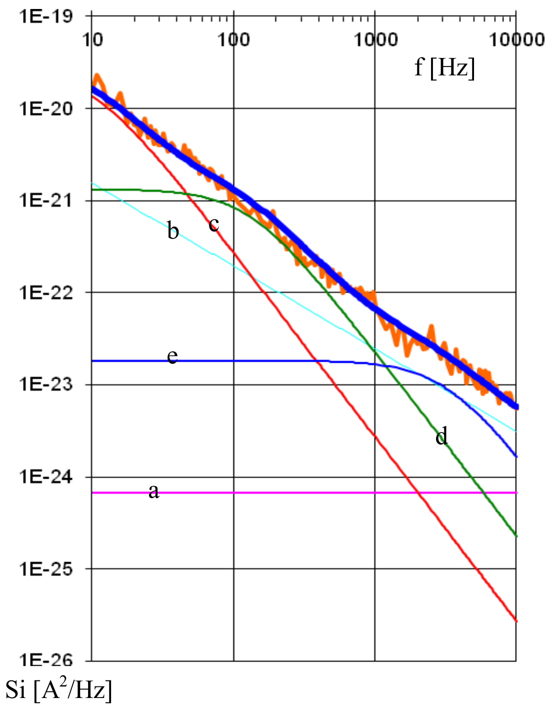

Fig. 7. Experimental results for current noise spectrum and fitting results according to Eq. (4) for resistor trimmed by high voltage pulses (Fig. 6, I = 0.2917 mA) with contributions of different kinds of noise sources in the total current noise spectrum (a - thermal current noise, b - 1/f noise, c, d, e - noise spectra of the Lorentzian shape).

In order to understand better the current noise related to high voltage pulse trimming of thick-film resitors, the fitting procedure shown in Fig. 6 was performed using experimental results and the following theoretical relation:

$$S_I(f) = A_0 + \frac{B_0}{f^\gamma} + \sum_i \frac{C_i}{2\pi f_{Ci}(1 + f^2 / f_{Ci}^2)}, \tag{4}$$

where A_0 is the thermal current noise, the second term is 1/f noise, and the third term is the sum of noise spectra of the Lorentzian shape. As an illustration, experimental and fitting results for resistor trimmed by high voltage pulses (I = 0.2917 mA) with contributions of different kinds of noise sources in the total current noise spectrum are given in Fig. 7.

It can be seen that 1/f noise is dominant in the total current noise spectrum. Sources of 1/f noise are sintered contacts, trap occupations and electrical charge fluctuations in insulator layers due to Nyquist noise modulation. Contribution of Lorentzian terms, correlated to fluctuations in number of electrons captured by traps in glass barriers, can be seen in forms of slight bands of $S_I(f)$ curve, mainly masked by 1/f noise but nevertheless influencing agreement of experimental results and Eq. 4. Performed experimental and numerical analysis of current noise spectra measured before and after resistor trimming by energy of high voltage pulses confirmed that trimming affects structural properties of the complex resistor network formed during sintering that lead to changes in electrical charge transport conditions. As a consequence, the value of the resistance can be gradually decreased in the controllable manner until the optimal value is obtained showing that the high voltage pulse trimming is a valid alternative resistance adjustment method.

3. Conclusion

In this paper effects of high voltage pulse trimming on structural properties of thick-film resistors are presented. Resistance, noise index and current noise spectrum measurements were performed before and after trimming of 10 kΩ/sq thick-film resistors. Performed experiments identified sources that have generated measured fluctuations caused by trimming. The examined trimming method caused irreversible resistance change due to changes in electrical charge transport conditions. It predominantly affected tunneling through glass barriers present in complex network formed during sintering by changing the barrier widths. Obtained results also confirmed that this type of trimming is a valid alternative trimming method to the dominant laser trimming method. The possible course of further investigations may involve thick-film resistors incorporated in sintered ceramic multilayer structures due to a fact that high voltage pulse trimming is the only applicable trimming method for these devices.

Acknowledgement

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Садржај: *Савремене компактне и поуздане електронске направе, укључујући керамичке микро-електро-механичке системе захтевају употребу отпорника све мањих димензија, стабилних и прецизних вредности отпорности. Из тог разлога се уместо ласерског тримовања за подешавање вредности отпорности дебелослојних отпорника све чешће користи поступак излагања отпорника високонапонским импулсима. Ова метода омогућава контролисано и поуздано подешавање вредности отпорности отпорника без присуства реза и без обзира на позицију и демензије отпорника. Међутим, он доводи до иверзибилних промена на нивоу структуре псеудослучајне мреже формиране током синтеровања, доводећи до измене механизама провођења. Из тог разлога смо у раду представили резултате експерименталног истраживања у коме су вредности отпорности дебелослојних отпорника подешаване енергијом високонапонских импулса. Добијени резултати су анализирани и утврђено је постојање везе између промена отпорности и параметара нискофреквентног шума са изменом механизама провођења у отпорницима услед дејства тримовања високонапонским импулсима. Идентификовани су извори измерених флуктуација и показано је да ова метода тримовања деболослојних отпорника представља валидну алтернативу ласерском тримовању.*

Кључне речи: *Дебелослојни отпорници; тримовање високонапонским импулсима; случајна отпорна мрежа; карактеристике структуре; маханизми провођесњ;, нискофреквентни шум.*