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Electron radiation effects on RuO_2-based thick-film temperature sensors

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The paper discusses the effects of electron radiation on resistance type Ru-based thick-film temperature sensors. Specimens, both commercial and lab made, were irradiated by the electron beam of the fluence from 5×10^{15} to 5×10^{17} e/cm^2. R vs. T characteristics were measured from 4 to 300 K before irradiation and after each radiation dose. Measurements show that sensors containing a higher amount of metallic phase (lower resistance) are more immune to radiation. This statement concerns also low frequency noise which was observed to increase less for low-resistance samples. Our conclusion is that the application of Ru-based temperature sensors in the radiation environment is limited to the low temperature region – below 20…25 K.

Keywords: RuO_2 thick-film resistors, temperature sensors, radiation effects.

1. Introduction

One of the applications of ruthenium-based thick resistive films is cryogenic thermometry. The reason of this is their good stability and high immunity to the magnetic field. However, low temperature sensors are also subjected to other environmental exposures, for example high and low pressure or ionizing radiation. While the influence of magnetic field results in reversible changes, the effects of radiation can result in irreversible changes of sensor parameters. In recent years more and more works appear that discuss immunity of the sensors to various types of radiation. It is related to the development in the research of high energy physics and the increased demand for temperature sensors insensitive to both magnetic field and radiation. In the paper the results of the measurements of RuO_2-based thick-film cryogenic temperature sensors exposed to electron radiation are reported. Our specimens were made from commercial and laboratory prepared resistive pastes and were irradiated by electron beam of the fluence in the range from 5×10^{15} to

5×10^{17} e/cm^2. Experiments like this have never been performed. The only data available in the literature and sensors manufacturers datasheets reefer to gamma and neutron radiation [1–5].

2. Experiment

Commercial pastes (produced by ITME, Warsaw) have sheet resistivity 1 kΩ/□ (R343 paste) and 10 kΩ/□ (R344 paste). The lab made pastes were composed of RuO_2 and lead borosilicate glass with 9% (v09) and 15% (v15) of RuO_2 by vol. Samples were made by standard screen-printing technology. Conductive and resistive pastes were deposited on alumina substrates and fired in a tunnel furnace. Resistive films made of commercial pastes have resistance 882 Ω (R343) and 8.6 kΩ (R344), respectively. The films made of the lab pastes have resistances 2.53 kΩ (v15) and 47.8 kΩ (v09). Before measurements all samples were preliminary aged by plunging in liquid nitrogen for a few minutes. The samples were irradiated at room temperature at a linear electron accelerator by electrons with 1 MeV energy. Radiation doses were from 5×10^{15} e/cm^2 to 5×10^{17} e/cm^2. To avoid sample heating under the electron beam, the density of the fluence was kept lower than 0.1 μA/cm^2. The special sample holder was used to deposit samples into cryostat for resistance measurements. Temperature characteristics were measured before irradiation and after each dose in the temperature range 4–300 K. The time of measurements in this interval was 10–12 hours. Resistance measurements were performed in two terminal configurations. The temperature in the cryostat was controlled and measured by calibrated GaAs *p–n* junction with the accuracy of 0.05 K. During resistance vs. temperature measurements neither cryostat nor temperature sensor were subjected to irradiation. To apply irradiation, the holder with the sample was removed from cryostat. Irradiated samples did not change their resistance at room temperature during a few days after each accumulated doze. For ITME samples, the noise intensity in the range 0–5 kHz was measured with the use of a direct current technique. These measurements were made before irradiation and after radiation by the total dose.

3. Results

The usefulness of temperature sensors exposed to radiation can be determined on the basis of their resistance changes. R vs. T characteristics for two samples with lower resistance are shown in Fig. 1. Differences in the shape of the characteristics in Fig. 1 are due to different composition of ITME and lab-made pastes. For high-resistance samples, $R(T)$ curves are similar to those in Fig. 1, except that no minimum was observed in the measured temperature range for v09 sample.

Samples R343 and R344 were exposed to electron fluences: 5×10^{15}, 1×10^{16}, 5×10^{16} and 1×10^{16} e/cm^2. Additionally, sample R344 was exposed to a dose of 5×10^{17} e/cm^2. Samples made from lab-made pastes were examined in the narrower irradiation range, namely only from 2.25×10^{16} to 7.25×10^{16} e/cm^2. As is shown in the figure, the $R(T)$

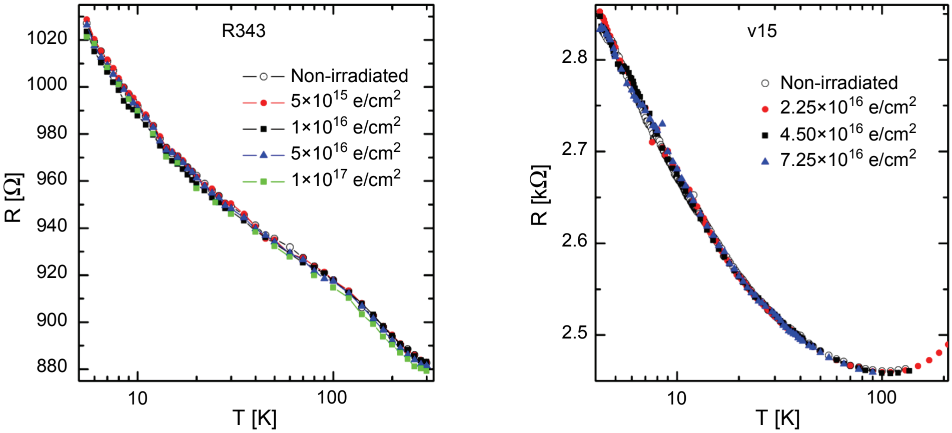

Fig. 1. Effects of radiation on temperature characteristics of R343 (ITME) and v15 (lab-made) samples.

curves for different radiation doses are close to each other and it is difficult to find any general dependence of resistance on the radiation. More information about this effect can be gained from Figs. 2 and 3 where relative resistance changes vs. irradiation dose are shown.

In general, for all our samples, resistance decreases with increasing irradiation dose. For both “ITME” samples, $|\Delta R/R|$ does not exceed 1% (Fig. 2). Up to the fluences of 10^{17} e/cm^2, relative resistance changes for sample R344 are about twice as large as for sample R343. Above the dose 10^{17} e/cm^2 resistance changes tend to saturate. This leads us to conclusion that sensors made from ITME pastes, supposed to operate in the radiation environment, should be calibrated only after the initial irradiation by a sufficiently high dose. This will reduce the radiation induced temperature reading error.

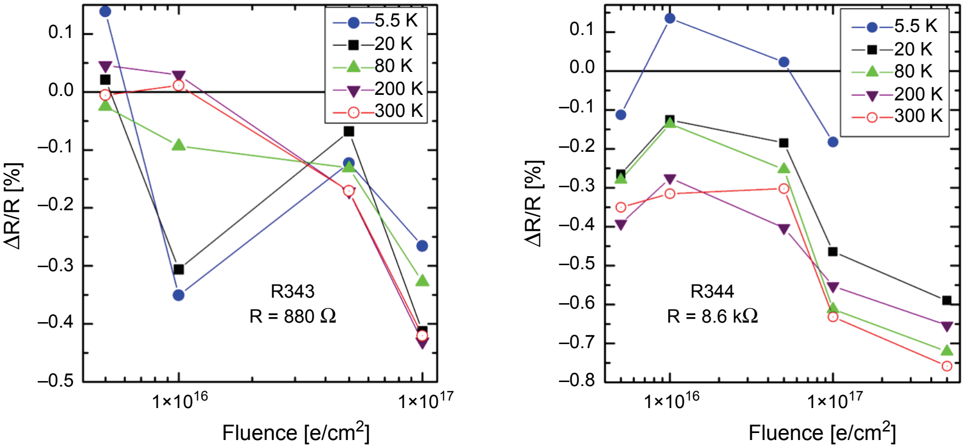

Fig. 2. Relative resistance changes vs. irradiation dose for samples made from ITME pastes.

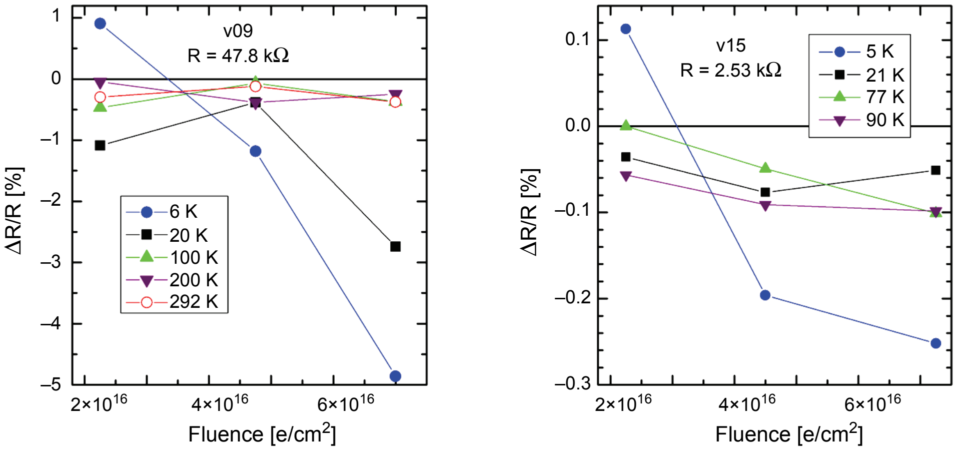

Fig. 3. Relative resistance changes vs. irradiation dose for samples made from lab pastes.

Samples made from lab-made pastes differ in the magnitude of $\Delta R/R$ caused by the radiation (Fig. 3). Sample v15, with lower resistance, is much more immune to electron radiation than sample v09. The largest relative resistance change observed for this sample at 5 K is 0.25%, while for v09 sample it is as much as 5%. At higher temperatures these changes do not exceed 0.1% and 0.5%, respectively. Even from these data it is easy to note that both samples exhibit larger resistance changes at lower temperatures.

For sensors users more practical information is the equivalent temperature error caused by environmental factors. This is because even quite large changes in sensor resistance will not cause significant error if the sensitivity of the sensor to changes

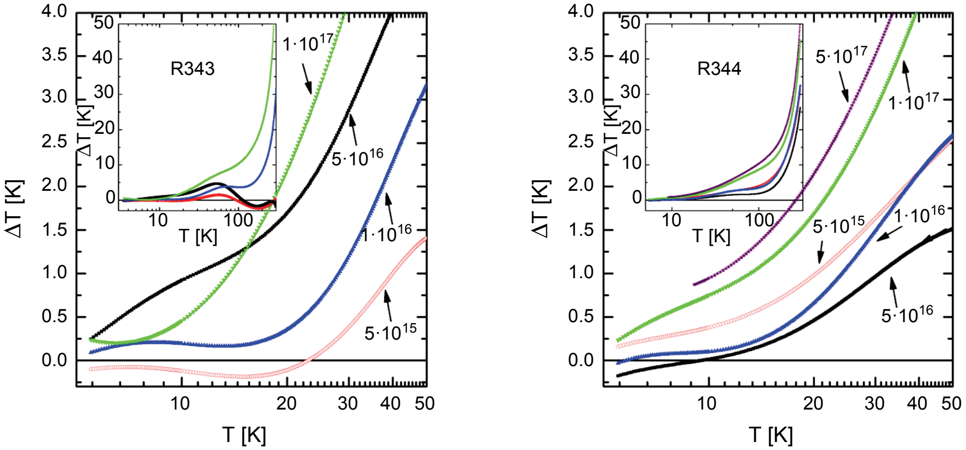

Fig. 4. Radiation induced temperature error for R343 and R344 samples.

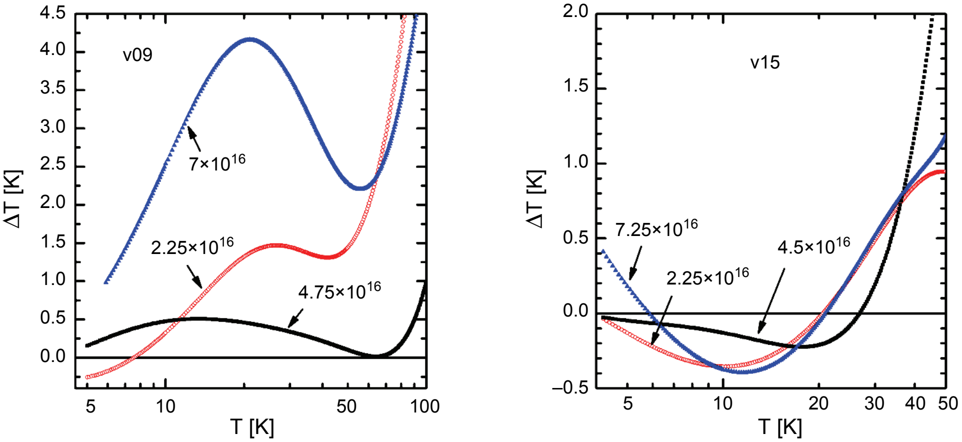

Fig. 5. Radiation induced temperature error for v09 and v15 samples.

in temperature is sufficiently larger. Radiation induced temperature error can be calculated as [1]

$$\Delta T(T) = \frac{\Delta R}{\mathrm{d}R/\mathrm{d}T} = \frac{R_{\mathrm{final}} - R_{\mathrm{initial}}}{\mathrm{d}R/\mathrm{d}T} \tag{1}$$

where R_{initial}, R_{final} refer to the resistance before irradiation and after each radiation dose, and $\mathrm{d}R/\mathrm{d}T$ is the sensor sensitivity. Temperature errors calculated according to Eq. (1) for all our samples are shown in Figs. 4 and 5. Prior to the calculations, the measured R vs. T data were smoothed by fitting with a sixth order polynomial:

$$y = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 \tag{2}$$

The polynomial coefficients for two samples are gathered in Tab. 1. As can be seen, the value of coefficient a_6 drops below few percent of a_1, so that further increasing of polynomial order is not productive.

It stems from Fig. 4 that for R343 sample and low radiation doses (5×10^{15} and 1×10^{16} e/cm^2) temperature error is almost constant below 20 K. Its absolute value does not exceed 0.2 K. For R344 sample ΔT increases slowly with temperature, reaching the value of 0.5 K at 20 K. For both samples, the temperature error increases sharply above 20–30 K. It is caused by decreased sensors sensitivity ($\mathrm{d}R/\mathrm{d}T$) in this temperature range. Small temperature errors are also observed for v15 sample (Fig. 5), despite its significantly lower sensitivity. The values of $|\Delta T|$ do not exceed 0.5 K for all radiation doses and below 30 K. For v09 sample, the values of ΔT depend much more stronger on a radiation dose and, in general, are several times larger. We can conclude that in the lab-made-paste-sensors the immunity to the radiation is more

Table 1. Values of the fitting polynomial coefficients for R344 (resistance fitted in Ω) and v09 samples (resistance fitted in kΩ).

Sample	Dose [e/cm^2]	a_0	a_1	a_2	a_3	a_4	a_5	a_6
R344	0	11656.5	–2425.93	4658.61	–6127.06	3901.89	–1230.90	153.406
	5×10^{15}	12787.4	–7755.96	14711.9	–15914.0	9059.46	–2625.78	304.988
	1×10^{16}	13425.96	–10290.8	18971.9	–19652.0	10849.6	–3067.66	348.837
	5×10^{16}	14530.7	–15683.4	29255.9	–29572.3	15987.4	–4431.396	494.619
	1×10^{17}	13448.2	–10096.7	17715.2	–17582.4	9333.76	–2550.86	282.165
	5×10^{17}	10928.6	22.2282	1184.26	–3569.84	2823.44	–975.979	126.904
v09	0	140.211	–125.200	98.0778	–74.0032	42.4282	–13.148	1.60027
	2.25×10^{16}	179.088	–227.812	184.055	–87.5211	25.5492	–4.37689	0.34743
	4.75×10^{16}	180.227	–298.873	390.648	–326.627	162.019	–42.7694	4.6071
	7×10^{16}	173.311	–234.925	194.103	–77.6813	10.1981	–1.88796	0.4932

influenced by the content of metallic phase (ruthenium dioxide) than in the ITME-paste-sensors.

An important parameter of any sensor is its resolution. For resistance type devices, it is determined by both thermal and 1/*f* noise of the sensor [6]. Flicker noise is also known to be an efficient diagnostic tool of defects density, failure prediction and a valuable indicator of device reliability [7]. For all these reasons low-frequency measurements were carried out. We aimed to find out the influence of radiation on noise level, so that our measurements were performed twice, *i.e.*, before irradiation and after total radiation dose.

Power spectral density, S_V, of excess noise of R343 and R344 samples was measured in the frequency range of 0–5 kHz for several bias voltages. Results are presented in Fig. 6 as a product $\langle f S_V \rangle$ vs. bias voltage. In log–log coordinates

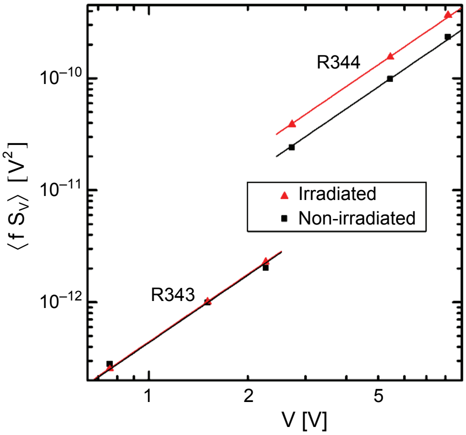

Fig. 6. Dependence of the noise magnitude $\langle f S_V \rangle$ on bias voltage before and after irradiation (ITME pastes).

Table 2. Values of current noise index measured before irradiation and after total dose (ITME pastes).

	CNI	
Samples	Before irradiation	After irradiation
R343	0.0199	0.0963
R344	8.87	10.86

the points lie on a straight line with a slope equal to 2, what proves that the noise is of a resistance type.

We are thus entitled to calculate current noise index (CNI):

$$\mathrm{CNI} = 10\log\left(10^{12}\frac{S_V}{V^2}\ln 10\right) \tag{3}$$

Its values are gathered in Tab. 2. In the R343 sample the radiation causes only a slight increase in CNI. In the R344 sample this increase is much higher.

Relative resolution ε_S connected to sensor's excess noise can be determined from CNI, according to relation [8]:

$$\varepsilon_S \cong \sqrt{\frac{S_V}{V^2}\ln 10} = \sqrt{10^{\frac{\mathrm{CNI}}{10} - 12}} \tag{4}$$

From data in Tab. 2 we can estimate that radiation makes the resolution poorer only by 25% for R344 sample and leaves it almost unchanged for low resistance sample R343. Thus our noise measurements are also in line with the earlier conclusion that resistors with higher ruthenium content are more immune to electron radiation.

4. Conclusions

In summary, our investigations show that Ru-based temperature sensors are highly immune to electron radiation and preserve their high-quality features at low temperature – below 20–25 K. Moreover we are able to conclude that:

– sensors with a higher content of metallic component exhibit higher immunity to the effects of electron radiation,

– sensors made of ITME pastes intended to be used in radiation environment should be preliminary irradiated before calibration,

– resolution of the sensors is weakly affected by irradiation.

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