Low Temperature Physics/Fizika Nizkikh Temperatur, 2021, vol. 47, No. 4, pp. 335–341

Long-term stability of TVO low-temperature sensors before and after gamma irradiation with a high dose

Yu. P. Filippov and V. M. Miklyaev

Joint Institute for Nuclear Research, Dubna 141980, Russia
E-mail: fyp@dubna.ru

V. V. Vainberg

Institute of Physics, National Academy of Sciences of Ukraine, Kiev 03680, Ukraine
E-mail: vainberg@iop.kiev.ua, viktor.vainberg@gmail.com

Received October 15, 2020, published online February 26, 2021

The long-term stability of well-known TVO sensors before and after gamma irradiation was investigated during almost 17 years. Five of six sensors, calibrated in the temperature range from 3 to 300 K, were selected according to a requirement of their relative accuracy $\Delta T/T \leq \pm 0.25$ % at the cryogenic temperature range. Long-term stability measurements made 7.5 years after calibration are in good agreement with this value at 293, 77.3, and 4.2 K. Then these sensors and the sixth sensor, taken as the "worst" one for comparison, were irradiated by the ^{60}Co gamma source at room temperature up to the total dose of about 1 MGy. Noticeable relative temperature shifts (more than ± 0.25 %) are revealed for all the sensors after irradiation, and this fact is explained based on the model of structural changes in the volume of the sensitive element. Post-irradiation measurements carried out during 9 years at 293, 77.3, and 4.2 K indicate good stability of the sensors after irradiation.

Keywords: TVO temperature sensor, low temperature, composite carbon material, gamma irradiation, radiation resistance.

1. Introduction

Superconducting installations require the systems to control the characteristics of cooling devices — magnets, cavities, detectors, etc., and to monitor the thermodynamic state of cryogens with relatively high accuracy. The temperature value is one of the main parameters to determine the state of a cryogen or a cooling device. While measuring the temperature, one needs to fulfill specific technical requirements which can be found in [1, 2], in particular, for XFEL (European X-ray Free Electron Laser) and ILC (International Linear Collider) projects. It is shown in [1, 2] that well-known cryogenic TVO (TVO is the transliteration of Russian abbreviation TBO meaning "Thermal-resistant Water-resistant Pressed") temperature sensors based on the composite carbon-alumina TVO resistor [3–6] could meet the necessary requirements. One can remind that its usual nominal resistances can be from 910 to 1100 Ω at room temperature, and the operating temperature range is from 0.1 to 425 K for the same sensor [6, 7]. It has good reproducibility, relatively small dimensions — a rectangular parallelepiped 1.3×2.4×8 mm of the fast thermal response of the order of 1 ms at 4.2 K, independence of magnetoresistance from orientation in the magnetic field, high electric isolation resistance — about 5000 MΩ and zero inductance. It is shown in [8] that two kinds of TVO resistors can be used to produce TVO temperature sensors. They differ in the technology of production and the color of ceramic coating — dark green or light green. This article concerns only TVO sensors of the first type since their quality is significantly better than for an analog of the second type [8].

The aim of this work was to estimate the long-term stability of TVO sensors before and after gamma irradiation that is interesting in the framework of the XFEL and similar projects. The scheme of the investigations was as follows. First, six sensors were calibrated in all the range from 3 to 300 K, and investigations of long-term stability were made 7.5 years after calibration. Then these sensors were irradiated by a ^{60}Co gamma source at room temperature up to a total dose of about 1 MGy. Thereafter, the post-radiation calibrations changes were measured at room

temperatures, in liquid nitrogen and liquid helium at atmospheric pressure during approximately sixteen months. At last, additional investigations on long-term stability were done 9 years later.

2. Experimental setup

To calibrate resistive temperature sensors, a special AK-6.30 calibrator was used [9], developed and manufactured jointly with the Department of Cryometrology of VNIIFTRI — one of the co-developers of the international temperature scale of 1990 (ITS-90). The calibrated sensors are inserted by means of a heat conductive grease into the copper comparison block located in a vacuum. The given temperature is measured with the reference rhodium-iron resistance thermometer RIRT-1 of VNIIFTRI calibrated with the accuracy of ± 1 mK for all the temperature range from 1 to 300 K; its resistance is about 100 Ω at 273 K. In accordance with the manufacturer's data sheet, the design of the comparison block and electronics allows one to provide the calibration uncertainty from ±2 to ±3 mK in the range from 1.5 to 300 K. Details can be found in the description of a similar nine-channel calibrator AK-6.25 [10] which differ from AK-6.30 only with the number of measuring channels. All the measurements and control functions, readout and processing of the obtained data are performed automatically by using AK-6 system and the special software compatible with IBM PC. The dc voltage measurement error due to nonlinearity is less than 0.002 %, and the relative error $\Delta R/R$ is less than 0.01 %. The overall accuracy of dc voltage measurement in the 10 mV-range is $\approx \pm 0.1$ μV, which is determined mainly by random error due to noise [10]. The measurement time is about 80 ms. All calibrations are traceable to the ITS-90.

A temperature monitor of own production [1, 11] is applied during the post-calibration procedure. A four-lead technique is used to measure the resistance of the temperature sensors with respect to the precision reference resistor. To avoid the influence of parasitic voltages, measurements are performed with a direct current source whose polarity can be changed. Up to fifteen measured resistive sensors can be connected to the T-monitor. The measurement time for all sensors is no more than 2 s. The electronic board includes, in particular, a direct current source with reversible polarity, multiplexers, reference resistors of 0.005 %, and ADC. The current value can be regulated from 0.5 μA to 5 mA. The used variant is supplied with reference resistors of 100 Ω and 1 kΩ which allow to measure the signals of the sensors whose resistance can be from 10 to 20 kΩ. The accuracy of measurements of the resistance is $\Delta R/R <$ < 0.01 %. The investigated TVO sensors were located in the 10-channel tested assembly with a thermal anchor to avoid the heat leakage through the wires of manganin of 0.15 mm in diameter. The temperature monitor software allows one to find the average resistance values (R-mode) and the average temperature values T(R) (T-mode) for repeated multiple measurements. Note that the average values of R_{av} for 10 measurements were used for measuring the resistances during the experiments. Comparison of R_{av} values with the resistance standards R_r-MS3006 of 100 Ω and 1 kΩ and 0.001 % accuracy showed that the difference $\Delta R = R_{av} - R_r$ did not exceed ± 0.005 and ± 0.05 Ω, respectively, for all measuring channels.

Platinum wire sensor PRT-7 of 100 Ω at 273.15 K was used during tests at room temperatures, its accuracy is about ± 0.01 K. To measure the signals of these sensors and check the multi-channel temperature monitor, the P3003M1-1 dc voltage comparator of 0.00025 % accuracy was used.

The irradiation experiment was carried out at the ^{60}Co gamma source with the energy of gamma quanta of 1.25 MeV up to the dose of 1033 kGy with the rather high dose rate of 1 Gy/s. While this experiment, 6 pieces of the calibrated TVO sensors were irradiated at the room temperature and then the post-irradiation measurements during 9-year period were made at the room, liquid nitrogen, and liquid helium temperatures.

3. Selection of sensors and long-term stability before irradiation

The TVO sensors were chosen in accordance with the following requirements. As noted, to obtain non-calibrated TVO temperature sensors, only TVO resistors of the first type, made before the year 2000 with dark green coating, were taken, since their characteristics are significantly better with respect to resistors produced after this date [8]. A method of preparating TVO sensors for heavy conditions was used in this experiment when the sensors were selected not only after the results on thermal cycling between the room and liquid nitrogen temperatures but also considering the full-scale calibration and fitting characteristics [2, 6]. Six sensors of different dimensionless sensitivities $S = (T/R)(dR/dT)$ at $T = 4.2$ K were selected for testing. Their resistances at room temperature were $R \approx (1100 \pm 55)$ Ω. The calibration characteristics $R(T)$ of the three chosen sensors are presented in Fig. 1 which demonstrates their different sensitivities dR/dT shown in Table 1.

One can note that, in principle, calibrated TVO sensors can be divided mainly into two groups considering their quality [8]: the 1st class of accuracy of $\Delta T/T \leq \pm 0.25$ % at 4 K < T < 120 K, $\Delta T = \pm 0.3$ K at 120 K < T < 300 K and the 2nd class of accuracy of $\Delta T/T \leq \pm 0.5$ % at 3 K < T < 100 K, $\Delta T = \pm 0.5$ K at 100 K < T < 300 K. Five of the six sensors

Table 1. Sensitivities of the sensors, dR/dT, presented in Fig. 1, at different temperatures

T, K	dR/dT, Ω/K		
	TVO 1	TVO 2	TVO 3
293	–0.70	–0.79	–0.69
77.3	–3.30	–4.14	–3.16
4.2	–472.5	–760.9	–348.9

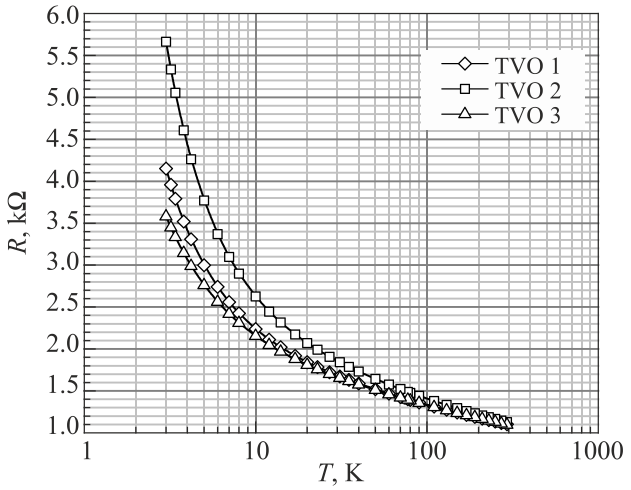

Fig. 1. Calibration characteristics $R(T)$ of some tested TVO sensors (# 1, 2, and 3 in Table 2).

were taken as the "good" sensors in accordance with a rather severe requirement $\Delta T_i / T \leq \pm 0.25$ %, where ΔT_i is the so-called initial temperature shift one week after calibration: $\Delta T_i = \Delta R_i / (dR/dT)$, where $\Delta R_i = R_{ac} - R_{dc}$ and *dc* and *ac* indexes refer to "during calibration" and "right after calibration". These measurements were carried out at two cryogenic temperatures: in Dewar's vessels with liquid nitrogen and helium at a fixed immersion depth of 0.1 m and a known saturation temperature $T_s(P_s)$, when the atmospheric saturation pressure P_s was measured with an absolute error not exceeding ± 50 Pa. Appearance of ΔT_i value is explained by the fact that the calibration is made in a copper block in a vacuum, and sensors are inserted into its holes using a thermally conducting grease. When the temperature drops, the grease freezes and compresses the sensor to be calibrated in a vacuum. During post-calibration testing, the pressure becomes atmospheric or so in liquid nitrogen and helium. The difference in mechanical stresses before and after calibration slightly varies which leads to the values of ΔT_i. These values are presented in Table 2 at different reference temperatures. If the sensor is installed on the pipe surface in a vacuum in the same casing as during calibration, the error associated with the installation method will be minimized. This method is used in the XFEL project [2].

Sensor #1 was selected as the "worst". Its $\Delta T_i / T$ relative shift was about 0.4 % at 4.2 K, and it was interesting to estimate its behavior during tests for comparison.

Long-term stability results 7.5 years after calibration are also shown in Table 2. These characteristics, ΔT_{lts}, differ in index "lts" — long-term stability. This value is found as $\Delta T_{\text{lts}} = \Delta R_{\text{lts}}/(dR/dT)$, where $\Delta R_{\text{lts}} = R_{7.5} - R_{dc}$, and indexes *dc* and 7.5 refer to "during calibration" and "7.5 years after calibration". One can see from Table 2 that the additional maximum temperature shifts 7.5 years after calibration in liquid nitrogen did not exceed $(\Delta T_{\text{lts}} - \Delta T_i) \approx -120$ mK (–0.15 %) for sensor #2 and 4 mK (0.1 %) for "worst" sensor #1 in liquid helium, for example. These shifts indicate good stability and agree with the results on long-term stability of the TVO sensors presented earlier [8].

4. Influence of irradiation

The results on irradiation influence are presented in Table 3. They are obtained 6 h after irradiation of the sensors up to gamma dose of 1.033 MGy, where ΔT_γ is the equivalent temperature difference between the measured temperature $T_m(R_m)$ and T_s or T_{PRT7}: all data are normalized to the constant temperatures 293, 77.3, and 4.2 K using the corresponding derivatives and possible differrences of the temperatures during experiments. Table 3 shows that the signs at the temperature shifts have changed mainly to the opposite at cryogenic temperatures with respect to the data on long-term stability, ΔT_{lts}, shown in Table 2.

The total temperature shifts due to gamma irradiation, $\Delta T_{\gamma t}$, are presented in Table 4 at different temperatures, where $\Delta T_{\gamma t} = \Delta T_{\text{lts}} - \Delta T_\gamma$, i.e., differences between the data before and after irradiation presented in Tables 2 and 3. Table 4 also shows the corresponding total resistance differences $\Delta R_{\gamma t} = \Delta T_{\gamma t}(dR/dT)$. The analysis has shown that based on the data from Table 4, one can highlight three varieties of *T*-sensors: "worst" — # 1, two "best" — # 2 and 4, and two "average" — # 5 and 6. Thus, the resistance of the "worst" sensor increased by 21 Ω at liquid helium temperature, and its growth in liquid nitrogen did not exceed 1 Ω whereas at room temperature this sensor demonstrated a small reduction of the resistance — by about –0.2 Ω.

Table 2. Initial temperature shifts, ΔT_i, and long-term stability, ΔT_{lts}, of the tested TVO sensors before irradiation at different temperatures

#	S(4.2 K) $(T/R)(dR/dT)$	ΔT_i, mK		ΔT_{lts}, mK		
		77.3 K	4.2 K	293 K	77.3 K	4.2 K
1	0.60	92	17	–60	118	21
2	0.75	–53	–2.5	–20	–172	–1
3	0.49	–98	–8	230	–173	–7
4	0.52	58	1	240	26	3
5	0.65	–122	–7.5	90	–224	–7
6	0.62	–112	–6.5	150	–203	–6.5

Table 3. Influence of gamma irradiation up to the total dose of ~1 MGy: the temperature shifts, ΔT_γ, 6 h after irradiation

#	ΔT_γ, mK		
	293 K	77.3 K	4.2 K
1	190	–155	–23.5
2	230	132	–2.5
3	30	135	5
4	20	–65	–5.5
5	160	185	4.5
6	100	165	4

Table 4. Total temperature shifts due to gamma-irradiation, $\Delta T_{\gamma t}$, and corresponding the total resistance differences, $\Delta R_{\gamma t}$, at different temperatures

#	$\Delta T_{\gamma t}$, mK			$\Delta R_{\gamma t}$, Ω		
	293 K	77.3 K	4.2 K	293 K	77.3 K	4.2 K
1	–250	273	44.5	0.18	–0.9	–21
2	–250	–304	1.5	0.20	1.3	–1.1
3	200	–308	–12	–0.14	1.0	4.2
4	220	91	8.5	–0.15	–0.3	–3.2
5	–70	–409	–11.5	0.06	1.8	7.1
6	50	–368	–10.5	0.04	1.6	5.9

In its turn, so-called "average" sensors # 5 and 6 showed the opposite change of resistances — decreased by approximately 6 to 7 Ω at helium temperature and about 1.7 Ω in liquid nitrogen, and their changes at room temperature are negligible. As for two "best" sensors (# 2 and 4), their resistances increased by approximately 1 to 3 Ω at helium temperature, but their changes in liquid nitrogen and at room temperature have opposite signs. That is, the unambiguous effect of irradiation on the characteristics of the sensors cannot be established that will be explained below.

5. Post-irradiation results

The ΔT_γ values from Table 3 were taken as zero points for the tested TVO sensors during the post-irradiation period. Corresponding results of measurements are shown in Fig. 2 during one month for different temperatures. One can see that the main changes occurred during the first week, and they look as diminishes of the post-irradiation values of ΔT_{pir} both at the room and liquid nitrogen temperatures. It means that the corresponding resistances are risen by 0.24 and 0.32 Ω for the "worst" (# 1) and "best" (# 2) sensors at room temperature and by 0.13 and 0.67 Ω for the same sensors in liquid nitrogen. In liquid helium, the changes in resistances are rather minor and do not exceed 3 mK for the "worst" sensor # 1 one week after the beginning of these measurements.

Further post-irradiation measurements during 15.5 months after irradiation are shown in Fig. 3. One can see that changes of the ΔT_{pir} values are rather small at all the temperatures. Thus, these values correspond to natural instability

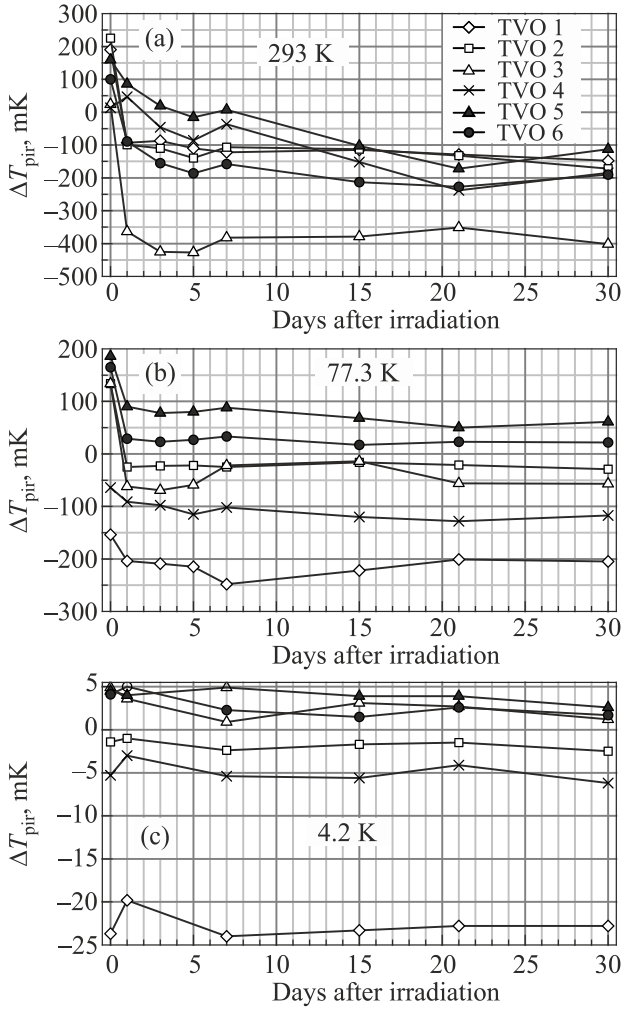

Fig. 2. Post-irradiation behavior of the tested sensors during the first month at different temperatures.

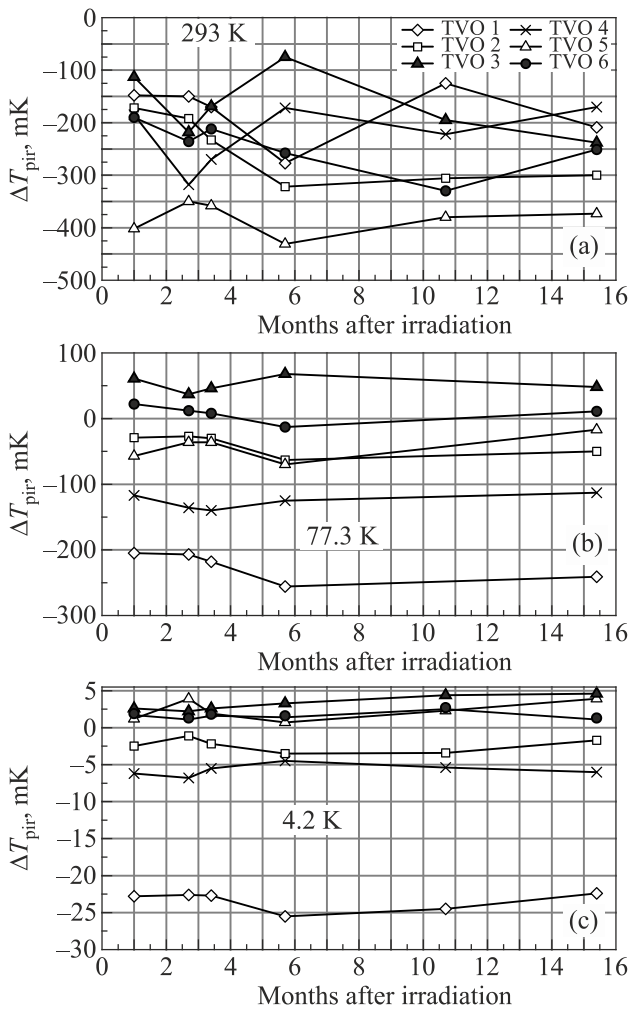

Fig. 3. Post-irradiation behavior of the tested sensors during approximately 15.5 months at different temperatures.

of the TVO resistors estimated as not more than ± 100 mK, ± 50 mK, and ± 3 mK (for a big batch of sensors), respectively, at room temperature, in liquid nitrogen and liquid helium at the atmospheric pressure. At room temperatures, additional influence is caused by inhomogeneity of air temperatures in the volume at 293 K with measured temperature sensors located in a thermostat with vacuum insulation.

6. Short-term and long-term stability after irradiation

Short-term (index "st") and long-term (index "lt") stability of the tested TVO sensors after irradiation are presented in Table 5 at different temperatures, where ΔT_{st} is the temperature shift with respect to initial calibrations approximately 15 months after irradiation (the last points in Fig. 3) and ΔT_{lt9} is the temperature shift approximately 9 years after irradiation. Table 5 shows that the values of the short-term (ΔT_{st}) and long-term (ΔT_{lt9}) stability at all the temperatures differ insignificantly, and their differences correspond mainly to the natural instabilities of the TVO resistors mentioned above.

Table 5. Short-term, ΔT_{st}, and long-term, ΔT_{lt9}, stability of the tested TVO sensors after irradiation at different temperatures

#	ΔT_{st} (293 K), mK	ΔT_{lt9} (293 K), mK	ΔT_{st} (77.3 K), mK	ΔT_{lt9} (77.3 K), mK	ΔT_{st} (4.2 K), mK	ΔT_{lt9} (4.2 K), mK
1	–209	–283	–241	–239	–22.4	–18.3
2	–300	–402	–50	–40	–1.7	2.3
3	–373	–451	–17	–38	3.9	5.8
4	–170	–340	–113	–134	–6	–2
5	–238	–140	48	60	4.6	7.5
6	–251	–362	11	–4	1.1	5.3

7. Discussion on behavior of defects

The TVO-sensor active element is made from the composite material consisting of the sintered mixture of the nanosized particles, being the carbon sp2-clusters, distributed in the matrix bulk of the micronized corundum powder. The carbon particle size is of 7 to 9 nm [12]. They are distributed nonuniformly in the form of hierarchical aggregations over the corundum matrix bulk [12, 13]. The electric transport in this case is determined by the electron states formed by dangling bonds, atoms shifted from their usual positions in the carbon particles and other defects both in the carbon particles and corundum. These states are localized and the conductivity is determined by the hopping mechanism and highly nonuniform potential relief [12, 13]. Irradiation by the high-energy γ-quanta results in forming new defects similar to those mentioned above. Also, in the course of γ-quanta scattering and recoil, the existing defects may disappear in a result of overcoming potential barriers and the shifted atoms return or dangling bonds recovery.

The modified temperature dependences of the resistance for the six studied TVO sensors are shown in Fig. 4, which

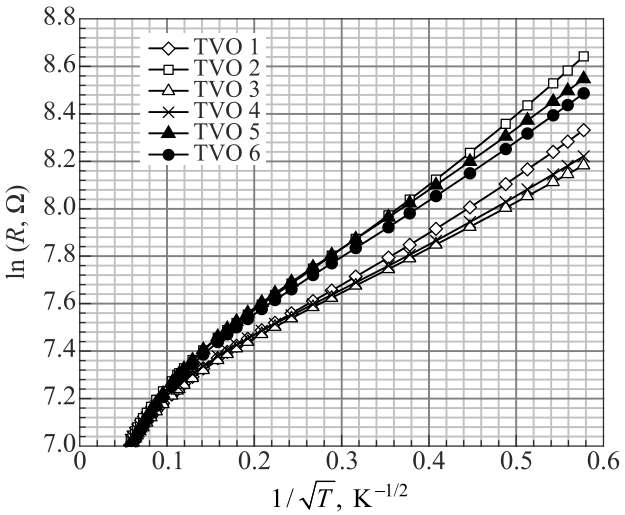

Fig. 4. Calibration dependences of the studied temperature sensors in coordinate system ln R versus $T^{-1/2}$.

confirms the hopping conduction mechanism dominating in the electric conduction of their sensitive elements [12]. These dependences are well described by the law $\ln R \sim \exp (T_0 / T)^{1/2}$ with the T_0 in the range from 4 to 7.7 K. They are qualitatively the same and quantitatively weakly differ in measurements before and after irradiation. It confirms that the conduction nature does not change in the result of irradiation and is characterized by the hopping mechanism described above. The difference in the T_0 magnitudes is caused by difference in the density of electronic states in the energy interval near the Fermi level and the localization radius characterizing the electrons envelop wave function decay outside the carbon particles. These parameters and, consequently, the resistances of sensors are highly sensitive to the structure changes. Irradiation by the γ-quanta, besides the creation of dangling bonds and other defects in the nanosized carbon aggregates, may generate additional charge carriers as well as the existing carriers may be captured in the traps. In turn, it also results in changing of the spatially nonuniform field of electric charges which determines the conduction parameters.

In principle, partly the appeared damages recover. They recover especially quickly at "high" temperature, overcoming the potential barriers. It is confirmed by the comparatively quick change of ΔT and, respectively, ΔR at the room temperature during a short period of time directly after irradiation [Fig. 2(a)]. The rest defects cannot overcome the energy barriers and this determines the residual deviation in the sensor calibration. At low temperatures, this recovery is difficult and in fact all deviations remain unchanged that corresponds to the discussed model. At that, only slow and negligible fluctuations are observed, reason of which is difficult to determine.

It is more difficult to explain the results for the so-called "worst" sample #1, whose calibration changes after irradiation and the residual deviation are the largest. Possibly it is

connected with the presence of quite strong stresses in this sample in the initial state remained after sintering of the corundum with the carbon nanoparticles. In this case, the high-energy γ-quanta, besides forming the own defects, may promote relaxation of stresses. In general, these changes are hard to foresee both by their sign and magnitude. Both kinds of changes may be specific to each sensor. It seems to depend on the extent of residual stress after their fabrication and reveals as some change of the sensor resistance, R, only after the high-energy treatment, for example, by γ-quanta irradiation.

8. Conclusions

TVO low-temperature sensors should be selected not only based on the results of thermal cycling in liquid nitrogen, but also based on post-calibration tests at room temperature, in liquid nitrogen and helium, depending on the requirements of their operation. The presented results are valid only for the sensors produced from TVO resistors fabricated before 2000 [8].

Five temperature sensors based on TVO resistors, selected for radiation testing in accordance with strict requirements ($\Delta T_i / T \le \pm 0.25$ % over the entire temperature range from 4 to 300 K), are characterized by high short-term and long-term stability for the 7.5-year period after calibration: their maximum relative temperature shifts do not exceed the values of $\Delta T_{\rm lts} / T =$ 0.1 % (293 K), $\Delta T_{\rm lts} / T = -0.3$ % (77.3 K), and $\Delta T_{\rm lts} / T = -0.2$ % (4.2 K). The sixth sensor with initial deviation $\Delta T_i / T = 0.4$ % (4.2 K), selected as the "worst" one for comparison, has shown the long-term stability of $\Delta T_{\rm lts} / T = 0.5$ % (4.2 K) 7.5 years after calibration.

Temperature shifts ΔT_γ were detected for the selected five sensors with low initial instability due to gamma irradiation by the ^{60}Co source up to an extremely high dose of about 1 MGy. The corresponding relative shifts do not exceed 0.1 % (293 K), ± 0.25 % (77.3 K), and ± 0.15 % (4.2 K) with respect to the initial temperature shifts, caused by slightly different calibration and post-calibration test conditions. These relatively small shifts in liquid nitrogen and liquid helium before and after radiation exposure are caused mainly by changing the sign in the value of the resistance deviation except the "best" sensor (#2) in liquid helium. The "worst" sensor (#1) also changed the temperature shift sign with a deviation of about ± 0.5 % (4.2 K).

The main changes in the calibration characteristics of all six sensors in the post-radiation period occurred during the first week. The maximum relative values of these shifts have not exceeded –0.15 % (293 K), –0.25 % (77.3 K), and 0.1 % (4.2 K). The relative long-term stability of the selected five sensors 9 years after irradiation does not exceed the values of $\Delta T_{\rm lt9} / T = -0.15$ % (293 K), $\Delta T_{\rm lt9} / T = \pm 0.2$ % (77.3 K), and $\Delta T_{\rm lt9} / T = \pm 0.2$ % (4.2 K). The "worst" sensor has shown quite acceptable long-term stability after 9 years — about –0.45 % (4.2 K).

Taking into account the change in the sign of the temperature shifts, the relative long-term stability for 16.5 years after calibration, including radiation damage due to a high gamma dose (about 1 MGy), has not exceeded ± 0.15 % (293 K), ± 0.3 % (77.3 K), and ± 0.5 % (4.2 K) even for the "worst" sensor. For the other five sensors, these indicators are noticeably better: not more than ± 0.2 % at 77.3 and 4.2 K. Thus, from our point of view, these sensors successfully meet the most severe known requirements even under the conditions of significant gamma irradiation.

The observed deviations in the calibrations of the TVO sensors caused by gamma irradiation and during a long-lasting subsequent relaxation period are in a reasonable agreement with the physical model of the hopping kind electric conduction in their sensitive elements. The parameters of this conduction, determined by the localized electron states and nonuniform potential relief in the composite carbon material, are modified because of formation and/or relaxation of the radiation defects in the course of irradiation by high-energy gamma quanta.

1. J. Trenikhina, T. Barnett, Yu. P. Filippov, and E. Yu. Filippova, *Proc. of the CEC-2007*, Chattanooga, USA, in: *Adv. Cryog. Eng*. **53B**, 973 (2008).
2. Yu. P. Filippov and V. M. Miklayev, *Proc. of the 23th International Cryogenic Engineering Conference* (*ICEC 23*), Wroclaw, Poland (2010), p. 537.
3. A. L. Lorente, C. Balle, J. Casas, E. Fortescue, P. Gomes, N. Jeanmonod, G. Peñacoba, and N. Vauthier, *Proc. of the 22th International Cryogenic Engineering Conference* (*ICEC 22*), Seoul, Korea (2008), p. 449.
4. M. Süßer, *Proc. of the 22th International Cryogenic Engineering Conference* (*ICEC 22*), Seoul, Korea (2008), p. 479.
5. M. Suesser, *Proc. of the 17th International Cryogenic Engineering Conference*, Bournemouth, UK (1998), p. 699.
6. Yu. P. Filippov and T. I. Smirnova, *Cryogenics* **44**, 735 (2004).
7. Yu. P. Filippov, G. G. Ihas, and V. V. Vainberg, *Rev. Sci. Instrum.* **80**, 094902 (2009).
8. Yu. P. Filippov and V. M. Miklayev, *Cryogenics* **100**, 85 (2019).
9. Yu. P. Filippov, A. M. Kovrizhnykh, V. M. Miklayev, and A. K. Sukhanova, *Cryogenics* **40**, 279 (2000).
10. F. Pavese, V. M. Malyshev, P. P. M. Steur, D. Ferri, and D. Giraudi, *Adv. Cryog. Eng*. **41B**, 1689 (1996).
11. Yu. P. Filippov, S. V. Alpatov, and B. N. Sveshnikov, *Proc. of the 20th International Cryogenic Engineering Conference* (*ICEC 20*), Beijing, China (2004), p. 955.
12. V. V. Vainberg, A. S. Pylypchuk, V. N. Poroshin, Yu. N. Gudenko, and A. S. Nikolenko, *Fiz. Nizk. Temp.* **45**, 1294 (2019) [*Low Temp. Phys.* **45**, 1104 (2019)].
13. V. V. Vainberg, A. S. Pylypchuk, V. N. Poroshin, and Yu. P. Filippov, *Fiz. Nizk. Temp.* **43**, 451 (2017) [*Low Temp. Phys.* **43**, 367 (2017)].

Довготривала стабільність низькотемпературних датчиків ТВО до та після гамма-опромінення високою дозою

Yu. P. Filippov, V. M. Miklyaev, V. V. Vainberg

Досліджено довготривалу стабільність відомих температурних датчиків ТВО до та після гамма-опромінення протягом майже 17 років. П’ять із шести відібраних датчиків, відкаліброваних в діапазоні від 3 до 300 К, було відібрано відповідно до вимоги їх відносної похибки $\Delta T/T \leq \pm$ 0,25% в кріогенному температурному діапазоні. Вимірювання їх довготривалої стабільності, проведені через 7,5 років після калібрування, показують добру згоду з таким критерієм точності при температурах 293, 77,3 та 4,2 К. Потім ці п'ять датчиків разом з шостим, взятим в якості «найгіршого» для порівняння, опромінювалися гамма-джерелом ^{60}Co при кімнатній температурі до сумарної дози близько 1 МГр. Після опромінення для всіх датчиків виявлено помітні відносні зсуви по температурі (більш ніж ± 0,25%), які пояснюються на основі моделі структурних змін в об’ємі чутливого елемента. Післярадіаційні вимірювання, проведені протягом 9 років при температурах 293, 77,3 та 4,2 К, свідчать про добру стабільність датчиків після опромінення.

Ключові слова: датчик температури ТВО, композитний вуглецевий матеріал, низькі температури, гамма-опромінення, радіаційна стійкість.