

Characterization of power transistors as high-dose dosimeters

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Abstract

A bipolar transistor, previously investigated as a possible radiation dosimeter and tested under industrial irradiation conditions in high-activity gamma and high-energy, high-power electron beam facilities has been subjected to stability test in order to understand its behaviour and help to improve its performances. Charge carrier lifetime was measured for several sets of transistors which were then irradiated with various doses (3-60 kGy): seven sets with ⁶⁰Co gamma rays and eight with a 10 MeV electron beam. After irradiation all the transistors were measured and each set was divided into three groups; one group was left untreated, the second group was heated at 100°C for 30 minutes and the third group was heated at 150°C for 30 minutes, for testing the stability of the lifetime. Our data showed that heat treatment quite successfully eliminates post-irradiation changes in the response. Response measurements of the irradiated transistors, heat-treated and untreated, were carried out at room temperature over several weeks after irradiation to establish post-irradiation stability and assess if these transistors could be used for recording dose history. Calibration curves in the range 3-60 kGy for the thermally treated and untreated devices are presented. Dependence of the response of the transistors on the temperature of the measurements in the range 20-50°C is reported.

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1. Introduction

It is quite essential for quality control in radiation processing that the measurements of absorbed dose are accurate and reliable [1,2]. In the radiation processing industry there is still a considerable interest in improving the accuracy and precision of existing dosimetry systems as well as in devising new, reliable, low cost, easy to use and improved ones. Among various dosimetric methods silicon devices were considered since many years both as radiation monitors at low doses, as in the field of radiation therapy, and at high doses, as for industrial radiation processes, because of the effect of ionizing radiation on the physical and electrical properties of these devices [3-6].

Considering that the reduction of the charge carrier lifetime is proportional to the irradiation dose, bipolar power transistors were tested, in previous works, as routine dosimeters under standard laboratory conditions [7], and in high-activity gamma and high-power electron beam facilities [8] with good results. This type of commercial bipolar transistors has a small size, low cost, and is easy to handle; but it was observed, when we started the present study, that the lifetime had post-irradiation recovery at room temperature. Since we are concerned primarily with dosimetric applications of these devices, this prompted us to study the long-term recovery behaviour of the lifetime of the gamma- and electron-irradiated transistors in order to find the optimum time intervals for evaluation of the lifetime after irradiation so as to overcome the recovery problem. To improve post-irradiation stability the transistors were submitted to post-irradiation thermal treatments at 100 and 150°C for 30 minutes and the effect of this treatment on the lifetime recovery behaviour was followed for two months storing them at room temperature.

The dependence of the lifetime measurements on the temperature was also studied in the range of 20-50°C.

Since the lifetime of the charge carrier is dependent on the type and concentration of the irradiation-induced defects in the silicon structure, deep level transient spectroscopy (DLTS) was performed on the irradiated transistors to identify the defects introduced by the radiation and the effect of the thermal treatment on them.

2. Materials and methods

2.1. Semiconductor device and its measuring circuit

The transistor used for this study is a commercially available, high voltage, fast switching n-p-n bipolar power transistor type BULT118 in plastic packaging with a sensitive area of 2.3 mm². Its characteristics have

been described by Fuochi et al. [7]. From previous studies it was found that the decrease of the charge carrier lifetime for this type of device is proportional to the absorbed dose [9], thus attention has been focused on this characteristic.

An easy-to-use and portable instrument described by Fuochi et al. [7] was used to measure a physical parameter T (storage time) related to the charge carrier lifetime τ and defined by the equation

$$T = \tau \ln(Q_s/\tau I_b)$$

where Q_s is the stored charge and I_b the turn-on base current.

The parameter T was measured in the temperature range 20-50°C by connecting the lifetime measuring circuit to a Peltier-effect thermocell. The response of the transistors to radiation was plotted against dose to water as measured by the reference dosimeters. Here the transistor response R is defined as:

$$R = 1/T_i - 1/T_0$$

where T_0 and T_i are the pre- and post-irradiation values.

2.2. Irradiation sources and procedures

Irradiation of transistors with gamma rays was done at the ISOF, Bologna, in the ^{60}Co Nordion Gammacell 220 having a dose rate of 10.6 Gy/min; irradiation chamber temperature during irradiation was 21°C. The transistors were enclosed in a plastic chamber with wall thickness of 0.4 g/cm², which is suitable for establishing electron equilibrium. The dose rate of the Gammacell for the reference geometry was determined with the alanine reference transfer dosimeters from Risø High Dose Reference (HRD) Laboratory with an expanded uncertainty of 2.8% at $k = 2$.

Electron irradiations were done in Warsaw using the Russian made 10-MeV Elektronika Linac at the INCT sterilization plant, the characteristics of which have been reported by Zimek et al. [10]. The transistors were placed in polystyrene phantoms from Risø HDR Laboratory [11] and irradiated by passing it through the scanned electron beam on a conveyor, such that the electrons were impinging on the copper side on which the silicon die is soldered. The absorbed dose to the transistors was determined by simultaneously irradiating graphite or polystyrene calorimeters, depending on the dose range, which are traceable to the UK National Physical Laboratory. The measured dose has an expanded uncertainty of 5.6% at $k = 2$. The mean temperature of the transistors during electron irradiation was about 20°C for the lowest dose (4.2 kGy) and up to 33°C for the highest (39.3 kGy). This value was calculated as the average of the temperatures before and after irradiation, which were measured with a calibrated thermistor embedded inside the polystyrene phantom.

All the absorbed doses referred in this paper are absorbed dose to water and were in the range of 3 to 60 kGy for gamma irradiations and 4 to 40 kGy for electron irradiation.

2.3. Deep level transient spectroscopy (DLTS)

The recombination centres introduced by irradiation in the silicon structure of the transistor were monitored and characterized by the DLTS using a high-sensitivity lock-in-type spectrometer [12] and the induced defect concentrations were determined by using a modified Zotha-Watanabe expression [13].

3. Results and discussion

3.1. Dose response

Several sets of transistors, each containing ten, were irradiated at various doses: seven sets with ^{60}Co gamma rays and eight with a 10 MeV electron beam. The changes in T for all the transistors following the irradiations were measured at 25°C. Soon after the measurements, each of the sets was subdivided into three groups; one group (two transistors) was left untreated, the second group (four transistors) was heated at 100°C for 30 minutes and the third (four transistors) at 150°C for 30 minutes. About 20 minutes after the end of the thermal treatment, when the transistors cooled down, the thermally treated transistors were re-measured at 25°C. Figures 1 and 2 represent the response functions where the transistor response R vs dose to water is plotted. Here the mean values of the response are plotted as well as the error bars which represent the standard deviation calculated for each group of transistors. All the data were analysed following the least squares fitting procedure. The second-order polynomial functions were selected based on the distribution of the percentage residuals. The correlation coefficient was 0.998 for all the three curves of electron irradiation while for gamma irradiation it was 0.994, 0.990, and 0.973 for the transistors untreated, thermally treated at 100°C and 150°C, respectively.

Since the coefficient of variation for the measured R values, for each absorbed dose, is an important parameter for establishing the useful dose range for a dosimetry system in the radiation processing applications, an analysis of these coefficients for the gamma- and electron-irradiated transistors was done. The results of this analysis show that for doses <5 kGy, the coefficient of variation for gamma- irradiated not heat-treated transistors is about 4%; for higher doses and for thermally treated ones, the coefficient of variation is $\leq 3\%$. For the electron-irradiated transistors, untreated and thermally treated, the coefficient of variation is <2% for all dose values studied.

The pooled estimate of the coefficient of variation for the estimated dose values calculated according to

ISO/ASTM 51707 [14] are listed in Table I.

3.2. Post-irradiation stability

An important factor in routine dosimetry is the time stability of the dosimeter response. Actually, any change over time in the dosimeter response can result in significant errors during routine use of the dosimeter; besides, the stability of the dosimeter response is essential for retrieval of recorded dose history from archives in case of auditing.

Post-irradiation stability of the lifetime of the irradiated transistors stored at room temperature (20-25°C, 50-60% RH) was studied before and after thermal treatment. The lifetime recovery, and hence the change of transistor response, for different dose levels were followed up to 47 days. The results for the irradiated transistors at doses around 10 and 30 kGy, not thermally treated, normalized to the first measurements taken about 20 minutes after irradiation, are shown in Fig. 3. Fitting of the data was done by a second-order exponential decay curve. The rate of change of the post-irradiated transistor response is high for the first 10 days, about 20% for the gamma- and 8% for electron-irradiated devices, and is dose independent. Subsequently it slows down significantly and the response tends to approach a constant value.

In contrast, our experimental data showed that these post-irradiation changes can be almost eliminated by heat treating the transistors, soon after irradiation, at 100 and 150 °C for 30 minutes. Table II reports the changes (%) of the response values over time after irradiation and heat treatment, compared with the first measurements taken at 20 minutes after heat treatment, for such transistors. The post-irradiation changes in the transistor response values for all conditions were found to be not very significant, namely $\leq 2\%$ and dose-independent. This value corresponds mainly to the uncertainty associated with the intrinsic transistor variability. However, there was one exception: the gamma-irradiated transistors at doses ≤ 10 kGy and heat treated at 150°C showed an increase in the response between 3% and 5.5% after 5 days, then levelling off to 3-4%.

The recovery of the lifetime of the irradiated transistors over time which did not undergo thermal treatment clearly indicates that the post-irradiation storage at room temperature changes their response (Fig. 3). It is believed that during storage, even at room temperature, some energy is available which is sufficient to remove shallow traps or trapping centres which are thermally unstable [15]. This is also confirmed by the fact that lifetime measurement leads to a small recovery of this quantity. The lifetime recovery after thermal treatment at 100° or 150°C can be interpreted as being due to partial annealing of deep traps that are introduced by radiation and to removal of surface damage and radiation-induced charge in the silicon

structure of the device. In order to corroborate experimentally this hypothesis DLTS measurements were carried out on transistors both as irradiated and post-irradiation thermally treated. Examples of these spectra are shown in Figs. 4 and 5 for a dose of about 20 kGy. The DLTS spectra of gamma-irradiated transistors (Fig. 4) clearly show the annealing of some defects and the appearance of other defects that are not produced directly by gamma-irradiation. This together with the removal of surface damage and radiation-induced charge could explain why the lifetime recovery is greater for the untreated and heat treated gamma-irradiated transistors compared to the electron-irradiated ones. The DLTS spectra of electron-irradiated transistors (Fig. 5) do not show changes with the thermal treatment as far as type of traps are concerned except for a small change in their concentrations. We believe that, in this case, annealing at 100 and 150°C causes mainly the removal of surface damage and radiation induced charge with little change in lifetime [16].

3.3. Temperature coefficient

The measurement temperature coefficients of the transistor response between 20 and 50°C are negative for all data sets. The value is approximately $(-0.60 \pm 0.03)\%/^{\circ}\text{C}$ for the electron-irradiated transistors and $(-0.6 \pm 0.1)\%/^{\circ}\text{C}$ for the gamma-irradiated ones with the exception of the transistors gamma-irradiated and thermally treated at 150°C for which the temperature coefficient is $(-0.8 \pm 0.1)\%/^{\circ}\text{C}$. As an example of the dependence of the transistor response on the temperature during the lifetime measurement, the data for the electron-irradiated transistors at 24.8 kGy are shown in Fig. 6 and similar behaviour was observed at all doses studied.

3.4. Intercomparison results

An intercomparison exercise was carried out with the Laboratory for Measurements of Technological Doses, Institute of Nuclear Chemistry and Technology (INCT), Warsaw using their ^{60}Co gamma ray source Issledovatel. The dose rate of this facility is traceable to NPL (Teddington) primary standard with an expanded uncertainty of 2.4% at $k = 2$. Two sets of four transistors from the same batch were irradiated to nominal doses of 3 kGy and 22 kGy. The parameter T of the irradiated not heat-treated transistors was measured at the ISOF Institute soon after they were received from Poland. Correcting for the recovery of the lifetime between the day of irradiation and that of the measurement, the ratio of the dose measured by the transistors and that given by INCT was 0.94 for the lower value of dose and 1.05 for the higher dose. Considering the total uncertainty, the agreement between these values is good; however, for the low dose the coefficient of variation was quite high, namely 8.4%. This confirms that these transistors are not suitable for determining doses below 5 kGy for applications where dosimetry is critical.

4. Conclusion

This study confirms that this type of transistors can be successfully used as routine dosimeters in electron and gamma facilities. However, it is critical that the dosimetric characteristics of each batch are carefully evaluated before using because lot-to-lot variations present an inherent source of variation in response of the transistors to irradiation. With respect to high-dose dosimetry applications, the post-irradiation change of the response is not of significant concern if the readout time for the calibration dosimeters is carefully standardized and selected and the same readout time is consistently used during routine processing. The post-irradiation heat treatment protocol for stabilization of the dosimeter response is desirable and even necessary for reliable dosimetry and if the dosimeters are to be archived for possible future readouts. Besides, where dosimetry is critical, as in the case of processes that concern public health and safety, it is suggested to perform measurement of the parameter T at a controlled temperature. Thermal treatment at 100°C seems to work better for the gamma-irradiated transistors as far as stability over time is concerned, while for the electron-irradiated transistors no significant differences were observed between the samples heat-treated at 100 and 150°C.

The thermally treated transistor can be used for archiving since the response is stable for months.

The useful dose range for these transistors is 5-50 kGy both for gamma radiation and electrons, as already reported by Fuochi et al.[8].

The main advantages of this dosimetry system are the low cost of the transistors, the relatively inexpensive readout system, ease of use, and the very short time to perform the dose measurement (few seconds for response reading after thermal treatment). Besides, while many radiochromic routine dosimeters present post-irradiation changes of the signal [17,18], the thermally treated transistors can be used for archiving, since the response is stable for months. As mentioned above it is advisable to perform measurements at controlled temperature; however, laboratory ambient conditions where the measurements are performed are generally quite adequate, and no other special precautions are necessary, except to limit the time that the transistor is held in hands while inserting it in the readout system.

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References

- [1] ISO/ASTM 51649:2005(E), Dosimetry in electron beam facility for radiation processing at energies between 300 keV and 25 MeV, in: Annual Book of ASTM Standards 12.02, Philadelphia, PA, USA, 2007, pp. 1094 1122.
- [2] ISO/ASTM 51702:2004(E), Dosimetry in gamma irradiation facilities for radiation processing, in: Annual Book of ASTM Standards 12.02, Philadelphia, PA, USA, 2007, pp. 1130 1139.
- [3] A.C. Muller, The "p" on "n" solar cell integrating dosimeter, in: N.W. Holm, R.J. Berry (Eds.), Manual on Radiation Dosimetry, Marcel Dekker, New York, 1970, pp. 429 433.
- [4] G. Rikner, E. Grussel, Phys. Med. Biol. 32 (1987) 1109 1117 (and references therein).
- [5] D.A.E. Ehlermann, Dose distributions and methods for its determination in bulk particulate food materials, in: K.W. Bögl, D.F. Regulla, M.J. Suess (Eds.), Health Impact, Identification and Dosimetry of Irradiated Foods, report of WHO Working Group, ISH-Heft 125 , Institut für Strahlenhygiene des Bundesgesundheitsamt, Neuherberg, 1988, pp. 415 419.
- [6] J. Barthe, Nucl. Instr. and Methods B 184 (2001) 158 189.
- [7] P.G. Fuochi, M. Lavallo, E. Gombia, R. Mosca, A. Kovács, A. Vitanza, A. Patti, On the use of a bipolar power transistor as routine dosimeters in radiation processing, IAEA-TECDOC-1070, IAEA-SM-356/47, International Atomic Energy Agency, Vienna, 1999, pp. 95 102.
- [8] P.G. Fuochi, M. Lavallo, U. Corda, S. Recupero, A. Bosetto, V. Baschieri, A. Kovács, Radiat. Phys. Chem. 71 (2004) 385 388.
- [9] P.G. Fuochi, Radiat. Phys. Chem. 44 (1994) 431 440.
- [10] Z. Zimek, H. Rzewuski, W. Migdal, Nukleonika 40 (1995) 93 114.
- [11] ISO/ASTM 51631:2003(E), Standard practice for use of calorimetric dosimetry systems for electron beam dose measurements and routine dosimeter calibration, in: Annual Book of ASTM Standards 12.02, Philadelphia, PA, USA, 2007, pp. 1086 1093.
- [12] D.V. Lang, J. Appl. Phys. 45 (1974) 3023 3032.
- [13] C. Ghezzi, E. Gombia, L. Vanzetti, Mater. Sci. Forum 10-12 (1986) 1213 1218.
- [14] ISO/ASTM 51707:2005(E), Standard guide for estimating uncertainties in dosimetry for radiation processing, in: Annual Book of ASTM Standards 12.02, Philadelphia, PA, USA, 2007, pp. 1140 1163.
- [15] J.W. Walker, C.T. Sah, Phys. Rev. B 7 (1973) 4587 4605.
- [16] R.O. Carlson, Y.S. Sun, H.B. Assalit, IEEE Trans. Electron. Dev. ED-24 (1977) 1103 1108.

[17] K. Farah, F. Kuntz, O. Kadri, L. Ghedira, Radiat. Phys. Chem. 71 (2004) 337 341.

[18] Z. Peimel-Stuglik, S. Fabisiak, Appl. Radiat. Isot. 66 (2008) 346 352.

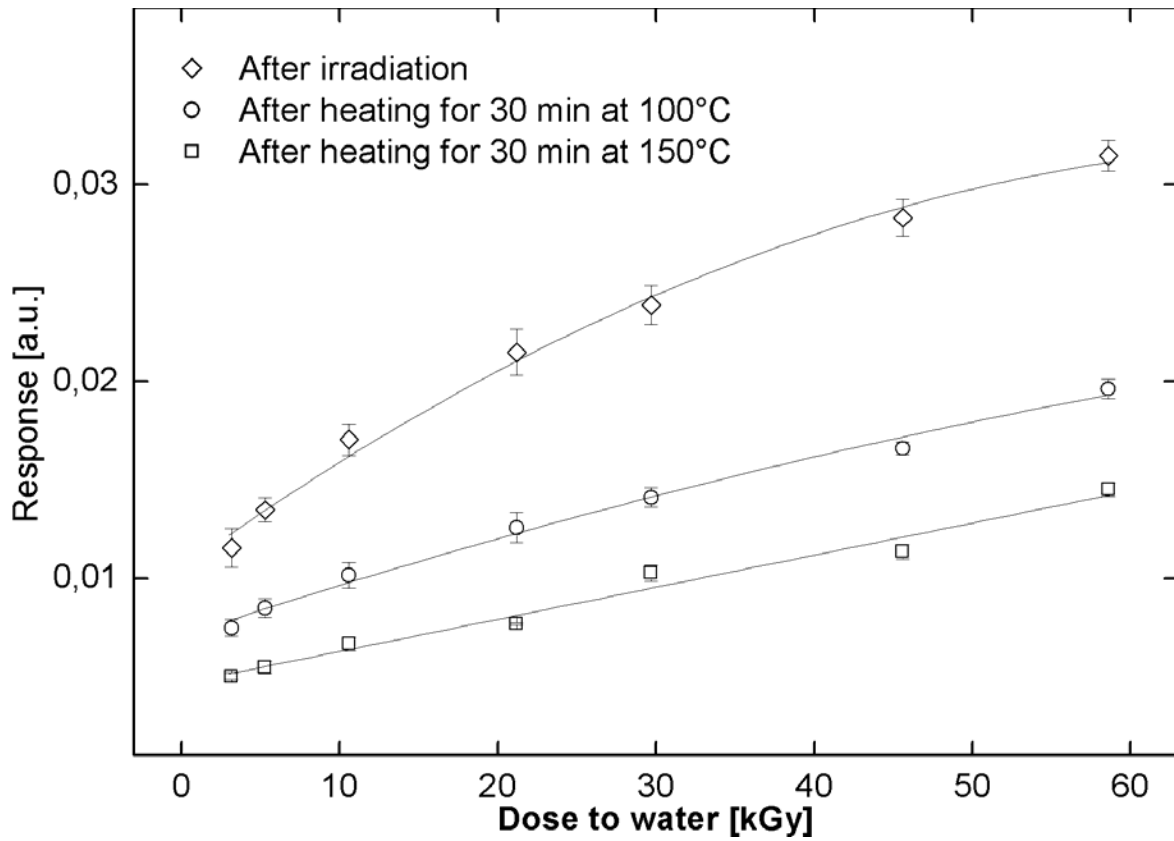


Fig. 1

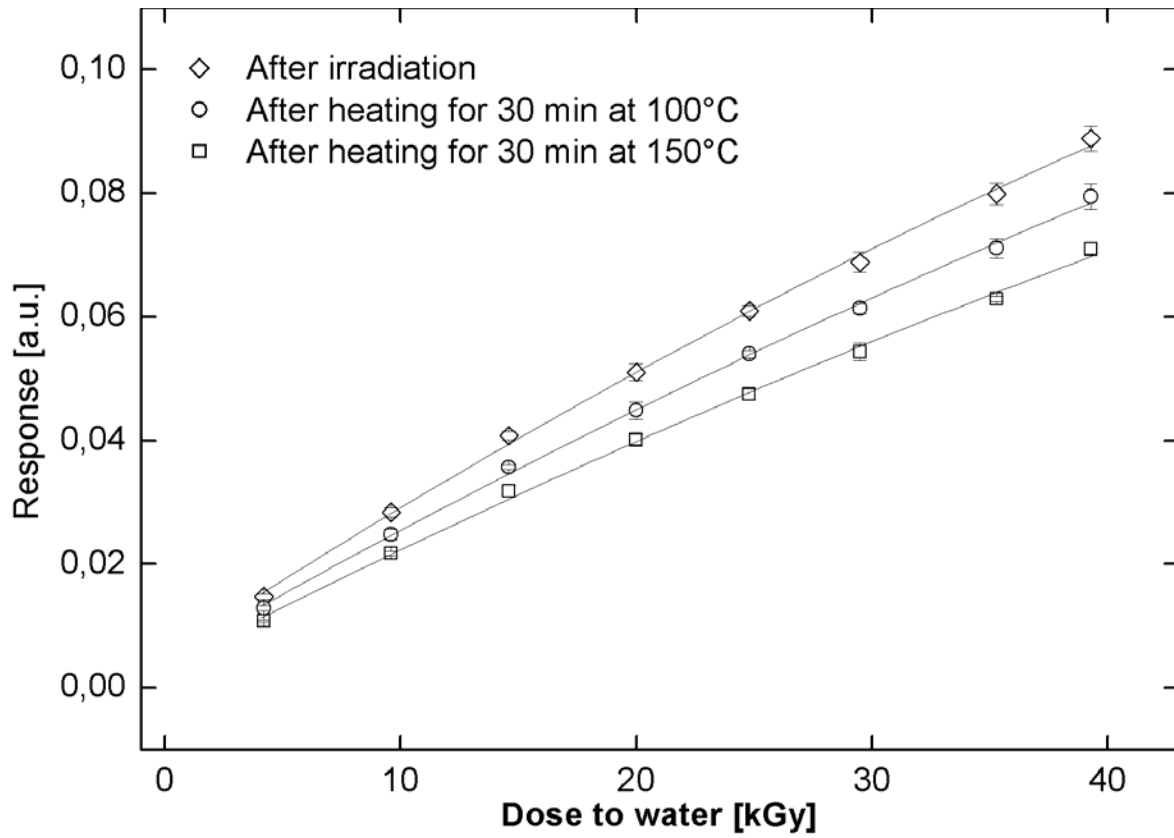


Fig. 2

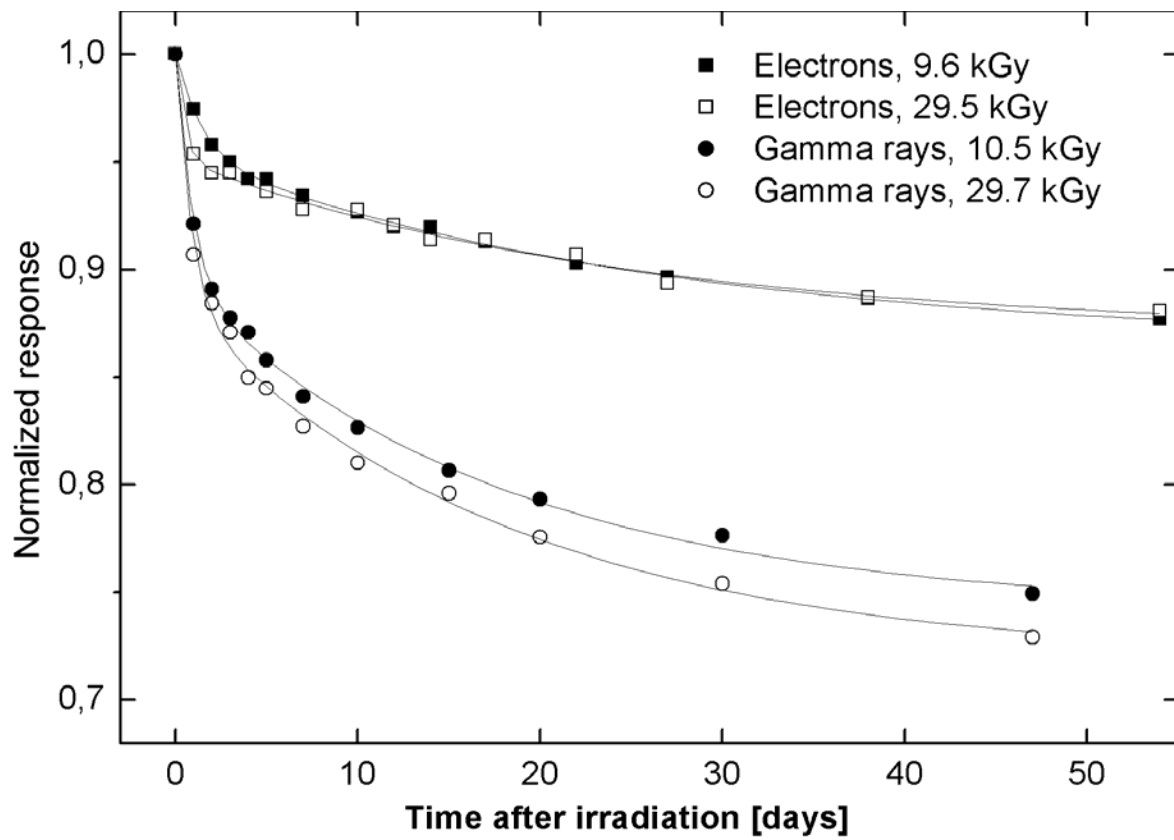


Fig. 3

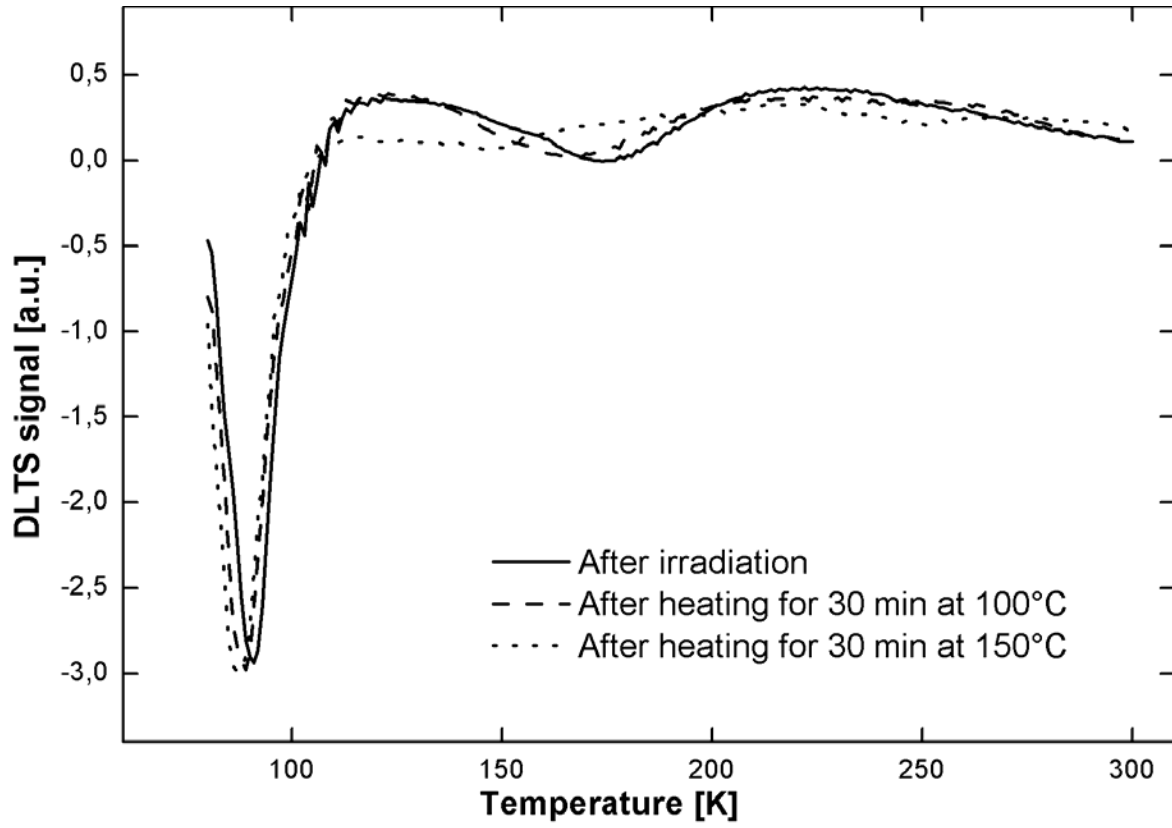


Fig. 4

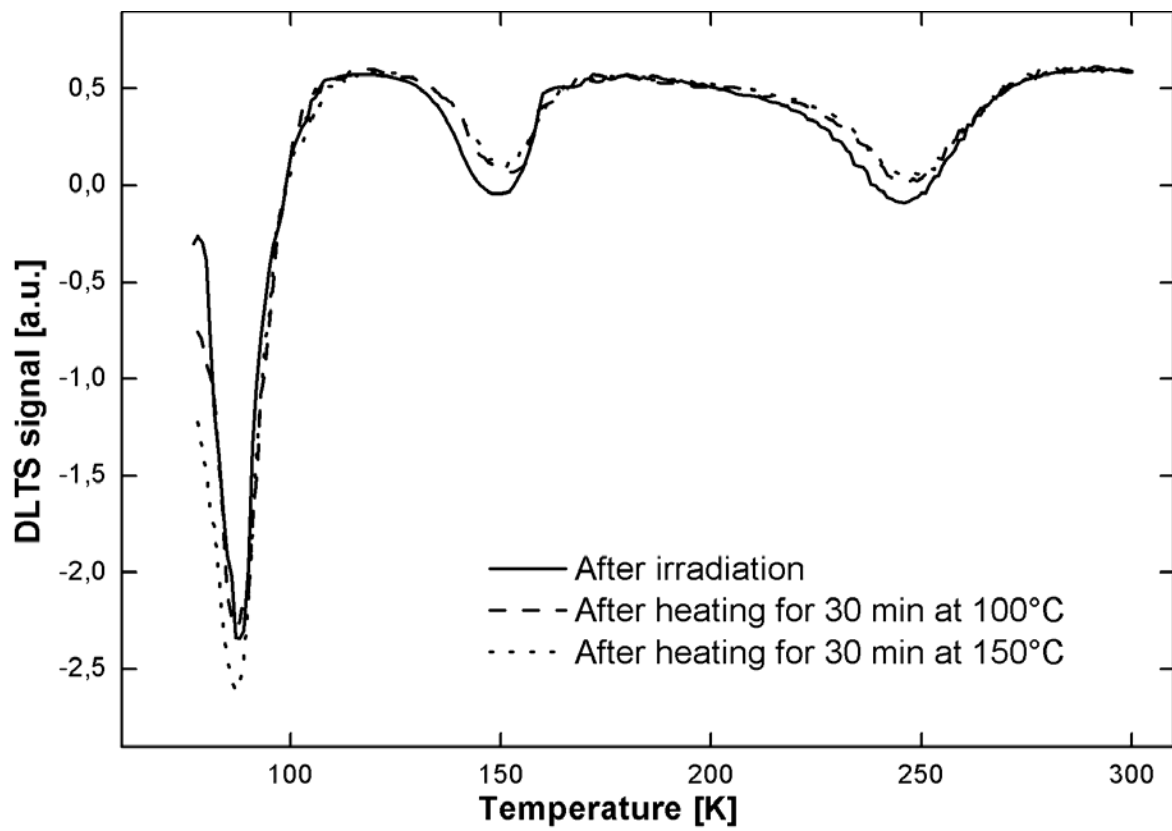


Fig. 5

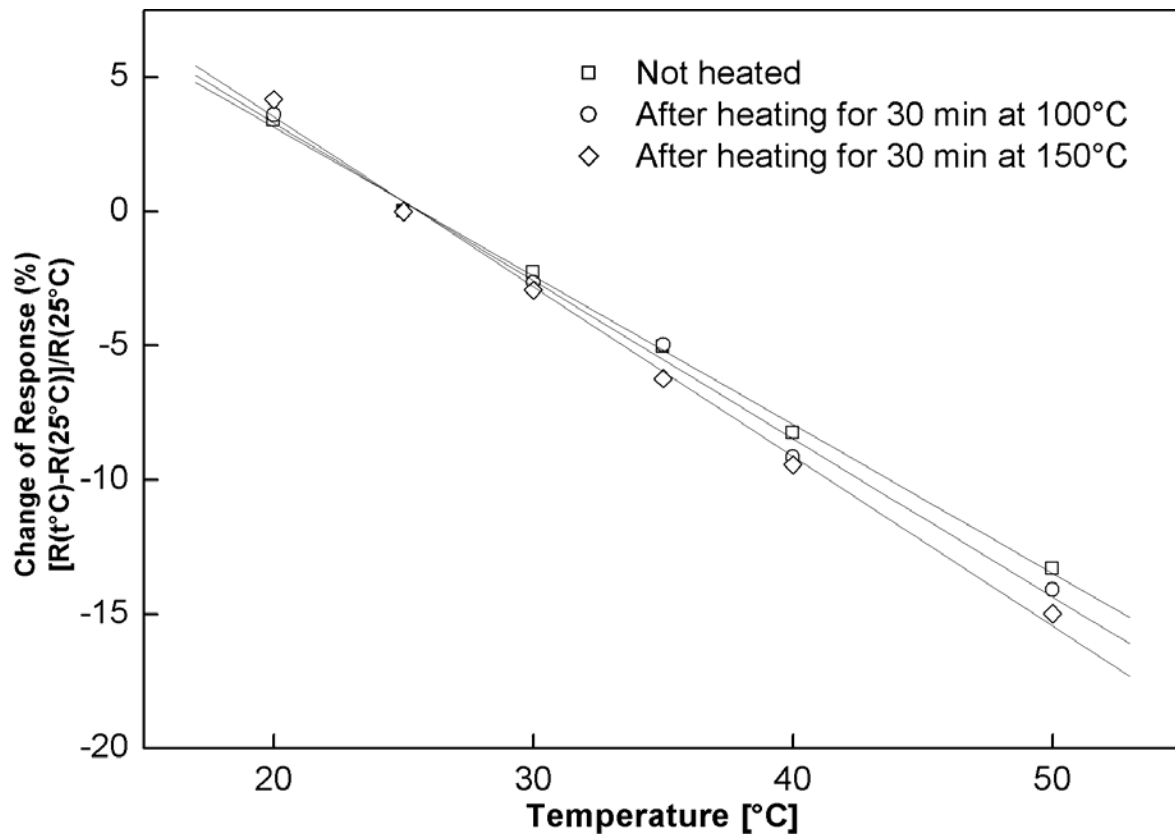


Fig. 6

Figure Captions

Figure 1. - Calibration curves for the transistor dosimetry system for ⁶⁰Co gamma rays.

Figure 2. - Calibration curves for the transistor dosimetry system for 10 MeV electrons.

Figure 3. - Post-irradiation recovery of un-treated transistor response irradiated with electrons and gamma rays at doses of about 10 and 30 kGy.

Figure 4. - DLTS spectra of gamma-irradiated transistors not annealed and annealed at 100 and 150°C for 30 minutes; dose 21.2 kGy.

Figure 5. - DLTS spectra of electron-irradiated transistors not annealed and annealed at 100 and 150°C for 30 minutes; dose 20.0 kGy.

Figure 6. - Dependence of the transistor response on the temperature of the measurement (samples irradiated with electrons at a dose of 24.8 kGy).

Table I. Pooled estimate of coefficient of variation (CV) for the estimated dose values for electron- and gamma-irradiated transistors

Irradiated transistors treatment	Electron CV (%)	Gamma *CV (%)
Not heated	1.6%	5.8%
100 °C for 30 minutes	1.6%	8.8%
150 °C for 30 minutes	1.2%	3.8%

*Not including the 3.2 kGy data.

Table II. Changes (%) of the transistor response over time after irradiation and thermal treatment

Dose [kGy]	10 MeV Electrons								Cobalt-60 Gamma rays								
	Annealed at 100°C				Annealed at 150°C				Annealed at 100°C				Annealed at 150°C				
	for 30 min				for 30 min				for 30 min				for 30 min				
	Days after irradiation*				Days after irradiation*				Days after irradiation*				Days after irradiation*				
	1	3	5	47	1	3	5	47		1	3	5	47	1	3	5	47
4.2	1.3	2.4	1.5	0.9	0.9	1.9	2.0	1.7	3.18	1.0	2.0	1.9	0.1	1.9	4.4	5.5	4.2
9.6	1.0	1.8	1.5	1.1	0.9	1.5	1.9	1.4	5.3	0.7	1.5	1.0	-0.2	1.1	3.6	3.9	3.4
14.6	1.1	1.3	1.6	1.4	0.3	0.6	0.8	1.2	10.6	0.9	0.7	0.8	-0.6	2.3	2.9	3.2	2.5
20.0	0.4	0.8	0.8	0.8	0.1	0.9	1.1	1.0	21.2	0.5	0.7	0.8	-1.2	-0.1	1.2	1.4	0.6
24.8	-0.9	0.0	0.5	0.0	-0.3	0.4	1.0	0.6	29.7	0.7	1.2	1.5	0.2	0.3	1.0	1.3	0.9
29.5	-0.9	-0.3	-0.2	0.0	-0.8	0.0	-0.2	-0.5	45.6	0.2	0.6	0.4	-1.0	0.7	1.5	1.5	1.1
35.3	0.0	0.6	0.4	0.6	0.0	0.5	0.7	0.5	58.6	0.5	1.6	1.2	0.7	0.6	1.9	1.5	1.3
39.3	0.0	0.7	0.2	0.9	1.0	-0.2	-0.4	0.6									

*Values relative to values immediately after irradiation and thermal treatment.

