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Radiation hardness of gas discharge tubes and avalanche diodes used for transient voltage suppression

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The widespread use of gas discharge tubes (GDTs) and avalanche diodes for transient voltage suppression (TVS) in many cases results in their exposure to ionizing radiation. The aim of this paper is to investigate the influence of irradiation on these TVS devices' characteristics, by exposing them to a combined neutron/gamma radiation field. Experimental results show that irradiation of TVS diodes causes a lasting degradation of their protective characteristics. On the other hand, GDTs exhibit a temporary change of performance. The observed effects are presented with the accompanying theoretical interpretations, based on the interaction of radiation with materials constituting the investigated devices.

Keywords: gas discharge tube; avalanche diode; radiation hardness; transient voltage suppression

1. Introduction

Transient surge voltages, either conducted or coupled, are a rather common occurrence in all electronic circuits, which makes efficient transient voltage suppression (TVS) a primary design requirement. Efficient protection against transient voltages, also called over-voltages, has two aspects: protection of integrity (no permanent damage of the protected device) and maintenance of operational functionality (operation reliability in the event of an over-voltage). Both power systems (providing energy generation, transmission and distribution) and low-voltage electronic systems are susceptible to transient voltages. The extent to which an electronic component can withstand a temporary over-voltage without damage is reduced significantly as components are miniaturized (*1*).

Gas discharge tubes (GDTs) belong to the *crowbar* group, whose operation rests on a switching action, such as the breakdown of a gas between electrodes, while avalanche diodes belong to the group of *clamping* TVS devices that dynamically adjust their impedance in order to maintain a constant voltage. GDTs and TVS diodes are complementary with respect to surge capability and response time. While gas tubes can withstand currents as high as 20 kA, semiconductor diodes

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are effective at currents up to 50 A. On the other hand, the response time of GDTs can go up to 5 μs, while TVS diodes have a subnanosecond response (*2*).

The use of modern electronic and electrical devices in conditions that imply exposure to ionizing radiation, *e.g.* at nuclear plants, in the military industry and in space technology, brings up the issue of TVS device radiation hardness. The aim of this paper is to investigate the influence of radiation exposure on the protective characteristics of commercial off-the-shelf (COTS) GDTs and TVS diodes. Only durable effects are considered, which are manifested both during and after irradiation. The investigation focuses on the operation of the devices immediately after irradiation, and the effects of long-term annealing are not treated. Radiation hardness of TVS devices is examined apart from that of any potential protected circuitry.

2. Operation principles and characteristics of the investigated TVS components

2.1. *Gas discharge tubes*

A GDT is a two-electrode symmetric component with gas insulation. Noble gases are mostly used as the insulating medium. The electrodes are sealed within a glass or ceramic tube, and typically separated by a gap of 3–4 mm. A cross-sectional view of a GDT with disc-shaped electrodes is shown in Figure 1(a). Operation of a GDT relies on the gas electrical discharge or breakdown,

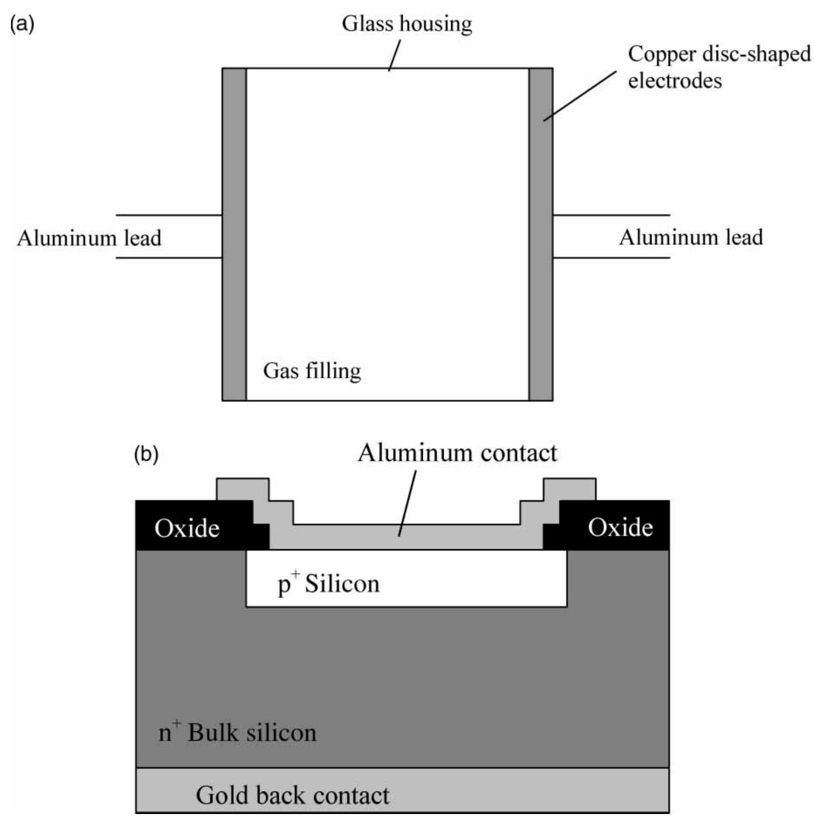

Figure 1. Cross-sectional diagrams of the investigated TVS devices: (a) gas discharge tube with disc-shaped electrodes and (b) avalanche diode.

arising from self-sustained avalanche processes dependent on the relative activity of electron generation and loss mechanisms. Gas electrical breakdown can be either static or dynamic.

Static breakdown occurs if the change of the rising voltage applied across the electrodes is much slower than the rate of the elementary processes leading to breakdown. The DC breakdown voltage is the voltage at which a gas tube starts to discharge during a static breakdown. It is a deterministic quantity, independent of the shape of the applied slowly rising voltage.

If a rapidly rising pulse voltage is applied across the electrodes, a dynamic breakdown occurs. Pulse breakdown voltage is the peak voltage present at the electrodes during a dynamic breakdown, at which gas electrical discharge starts. It is a stochastic quantity that can be represented as a random variable. The value of the pulse breakdown voltage varies depending on the steepness of the voltage applied to the tube. The curve showing the relationship between the pulse breakdown voltage and the time required for the breakdown to begin is called a $V-t$ characteristic (*3*, *4*).

When used for TVS, a GDT is connected in parallel to the protected component. GDTs are largely used for protecting circuits in telecommunications (where electromagnetic interference (EMI) events can be induced in many ways, including lightning), as well as in high-voltage engineering (where switching over voltages may arise as a consequence of energy redirection within a power system). The protective ability of a GDT against rapidly rising surge voltages depends on its $V-t$ characteristic.

2.2. *Avalanche diodes*

A TVS avalanche diode is designed to go through avalanche breakdown at a specified reverse bias voltage, and thereby clamp a transient surge pulse. Turn-on voltages of silicon avalanche diodes can be over 4 kV. Below the turn-on voltage, a TVS diode has high impedance and functions as a capacitor. At voltages above turn-on level, the device functions as a variable resistor that is dynamically controlled to maintain a constant clamping voltage. Avalanche breakdown is not destructive, as long as the diode is not allowed to overheat. Figure 1(b) provides a cross-sectional view of a TVS diode. TVS avalanche diodes dissipate energy in the relatively narrow junction depletion region. They are therefore typically designed to have a large junction area, which provides the ability to absorb high peak energy (*2*).

TVS diodes provide a way to increase the immunity of a circuit to EMI and electrostatic discharge (ESD). Most integrated circuits (ICs) contain internal surge protection circuits that function well at preventing ESD failures that occur in assembly. However, they are often inadequate for protecting against surge events that occur in normal product usage. The ability of a TVS diode to sustain surges is directly related to its size, and external devices are typically 10 times larger than the internal IC TVS devices. External TVS diodes are usually used when a more reliable surge protection is desired, because it is not practical for an IC to incorporate large protection devices. In addition, the internal protection circuit of most ICs is designed to handle only a few ESD events, while an external TVS device provides immunity for an indefinite amount of surges (*5*).

Both GDTs and avalanche diodes are nonlinear components. The relationship between the current in a nonlinear component I and the voltage across its terminals U is typically described by a power law $I = kU^{\alpha}$, where k is a proportionality constant, and α the nonlinearity coefficient which was used in this paper to monitor radiation induced changes in TVS avalanche diodes.

3. Experimental

The measuring equipment consisted of a radiation source, a programmable current source (providing pulsed currents up to 5 A at 3 kV maximum voltage), a high-voltage pulse generator (10 kV maximum voltage, with a repetition rate up to 10 kHz), a digital oscilloscope (Agilent 54510A, 250 MHz) and a personal computer. The experimental procedure was fully automated. A specialized PC-based software was developed to provide specification and control of parameters, as well as data acquisition, using the IEEE-488 protocol. All experiments were performed at room temperature (25°C).

The source of a combined neutron/gamma radiation field, used to irradiate the tested TVS devices, was a ^{252}Cf isotope, encapsulated in the form of Cf_2O_3. The mass of the ^{252}Cf radionuclide was 2.265 μg, and its specific neutron and gamma emission rates were $2.34 \times 10^6\ \mu g^{-1}\ s^{-1}$ and $5.3 \times 10^9\ \mu g^{-1}\ s^{-1}$, respectively. The average neutron energy of the ^{252}Cf source is 2.14 MeV, and the average gamma photon energy 0.88 MeV.

A neutron survey meter with excellent gamma rejection, calibrated relative to a standard ^{252}Cf source, was used to measure neutron dose rates at various points in the vicinity of the source used for the experiments. The desired absorbed doses were specified by changing the duration of irradiation and the distance between the source and the examined devices.

A COTS argon-filled discharge tube, with disc-shaped copper electrodes and a 750 V nominal DC breakdown voltage was used for testing GDT radiation hardness. The test method consisted in applying a series of 20 slowly rising pulses (2 kV/s) to the tube, causing static breakdowns, followed by a series of 50 double-exponential voltage pulses (1 kV, 1.2/50 μs) causing dynamic breakdowns, before exposure to radiation and after each absorbed dose increment, with a 30 s pause between consecutive pulses. The radiation field was not present during the breakdowns. GDT characteristics presented in the paper are based on the mean values calculated for each breakdown series.

COTS avalanche silicon diodes with 250 V nominal turn-on voltage were used for the experiments. Measurements were performed on a sample consisting of 30 diodes. Diode characteristics presented in the paper are based on sample mean values. The diodes were all produced by a single manufacturer, with identical nominal characteristics, which resulted in low statistical dispersion of the obtained results. Experiments consisted in applying double-exponential current pulses (13 A, 8/20 μs) to the reverse-biased diodes to simulate surge waves, and recording diode voltage response after each absorbed dose increment. The radiation field was not present during the testing of diode response.

4. Results and discussion

4.1. *Irradiation effects in GDTs*

Radiation-induced effects on the GDT's operation were examined by monitoring the values of its DC breakdown voltage and calculating its $V-t$ characteristics, as the absorbed dose was raised. Determination of $V-t$ characteristics was based on the Area law (*6–8*).

An exact experimental determination of the $V-t$ characteristic would require voltage pulses with different slopes of the rising edge to be applied. However, the Area law states that, when the dynamic breakdown occurs, whatever the slope of the applied voltage, there is a constant geometrical area formed in the voltage-time plane between the electrode voltage waveform $u(t)$ and the level of the DC breakdown voltage U_b^{DC}. This is expressed by the following equation:

$$\int_{t_0}^{t_d} \left[u(t) - U_b^{\mathrm{DC}}\right] dt = P = \text{const}, \tag{1}$$

where integration is performed over time from the moment t_0, when the voltage at the electrodes reaches the value of the DC breakdown voltage, to the onset of gas discharge at t_d. The Area law thus provides a way of calculating a semi-empirical expression for the $V-t$ characteristic, after the values of the DC breakdown voltage and the pulse breakdown voltage for a single slope of the voltage applied to the tube are measured (*3*).

The GDT DC breakdown voltage mean value was calculated at every absorbed dose level, based on the results obtained from the 20 static breakdowns. Since the pulse breakdown voltage is a random variable, instead of obtaining a single mean value for it, 99.99 and 0.01% quantiles were calculated from the 50 dynamic breakdowns produced with the aforementioned double-exponential voltage pulses. Based on these results and the Area law, the 99.99 and 0.01% quantiles of the $V-t$ characteristics were derived.

The GDT was subjected to neutron absorbed doses ranging from 0.1 to 1.2 Gy, with a 0.1 Gy increment. Figure 2 shows the GDT DC breakdown voltage U_b^{DC} versus the absorbed dose. In Figure 3, $V-t$ characteristics corresponding to 99.99 and 0.01% quantiles of the GDT pulse breakdown voltage are presented. For better clarity of the plots, $V-t$ characteristics are only shown for certain values of the absorbed dose. Experimental results show that irradiation of the GDT caused a decrease in its DC breakdown voltage. On the other hand, as the absorbed dose increased, the pulse breakdown voltage of the GDT became lower and its dynamic response more rapid, as seen from the lower position of the $V-t$ characteristic quantile curves at higher doses. Statistical dispersion of the pulse breakdown voltage also decreased, as observed from the nearing of the corresponding 99.99 and 0.01% quantile curves. Hence, from the point of TVS, if the observed drop of the DC breakdown voltage is within tolerable range for a specific application, protective characteristics of the GDT were improved after exposure.

The observed radiation effects in the GDT can all be attributed to the higher availability of free electrons in the inter-electrode gap capable of initializing the discharge. Radiation to which the GDT is exposed causes activation of the tube's components, primarily its glass housing and copper electrodes, producing radionuclides that are beta and gamma emitters. This induced radiation, which is present even after the outer radiation field is eliminated, causes ionization of the gas in the tube, resulting in the higher concentration of free electrons. For neutron and gamma ray energies of the used ^{252}Cf source, comparison of the corresponding cross-sections

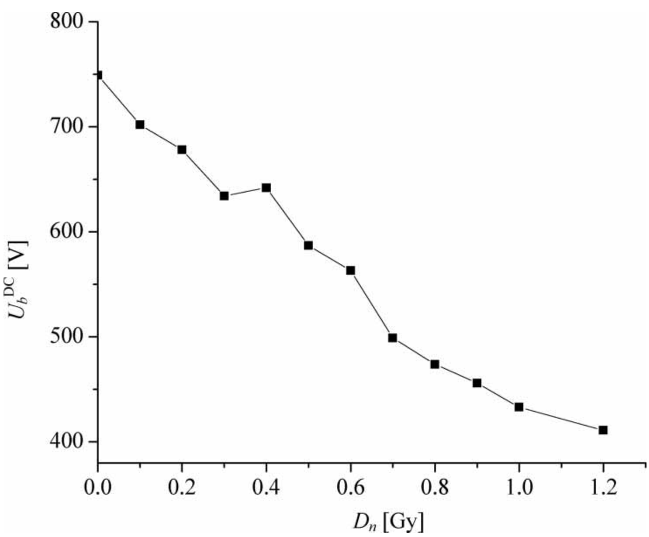

Figure 2. GDT DC breakdown voltage versus neutron absorbed dose.

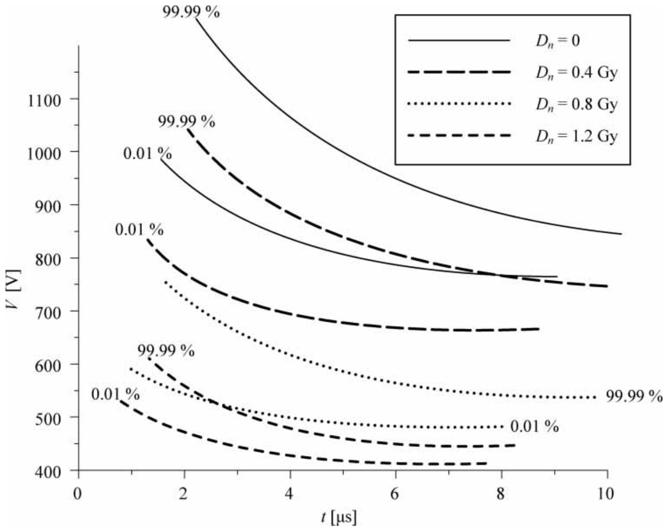

Figure 3. Quantiles (99.99 and 0.01%) of the GDT's $V-t$ characteristic at different absorbed doses.

for various nuclear reactions suggests that the activation of the tube's construction materials is almost entirely due to the neutron component. The gamma component of the radiation field could have otherwise influenced GDT's electric properties only during the course of irradiation through direct ionization of the gas (*9–12*). These facts allowed only the neutron absorbed dose in argon to be presented with the results in Figures 2 and 3.

Results of the gamma-spectrometric activation analysis of the irradiated GDT, performed immediately after the completion of irradiation, are presented in Figure 4(a). Characteristic peaks of neutron activation products, such as ^{56}Mn, ^{87}Kr, ^{27}Mg, ^{23}Fe, ^{60}Cu and ^{65}Zn, are clearly noticeable. The identified radionuclides, arising from neutron nuclear reactions occuring in materials comprising the tube, were confirmed to be both beta and gamma emitters. The change of GDT's protective characteristics caused by irradiation lasts only for a certain period of time. The half-lives of much of the induced radionuclides are under several hours. Another gamma-spectrometric measurement performed 6 h after irradiation (results of which are shown in Figure 4(b)), demonstrates that virtually all activation products have completely decayed. An additional measurement of GDT's DC and pulse breakdown voltages, performed 10 h after the last irradiation, showed that the device recovered to the pre-irradiation state (*13–15*).

4.2. *Irradiation effects in avalanche diodes*

The influence of the neutron/gamma radiation field on the TVS diodes' operation was investigated by monitoring the diode turn-on voltage U_t, volt–ampere (U–I) characteristic (measured at five points, with the diode in the breakdown regime, and the inverse current ranging from 2 to 13 A), and the nonlinearity coefficient α, calculated as:

$$\alpha = \frac{\log I_2/I_1}{\log U_2/U_1}, \tag{2}$$

where (U_1, I_1) and (U_2, I_2) are points taken from the volt–ampere curve.

TVS diodes were exposed to 10 different levels of neutron absorbed dose in silicon D_n, ranging from 0.1 to 1 Gy, with a 0.1 Gy increment. Figure 5 shows experimentally observed changes in

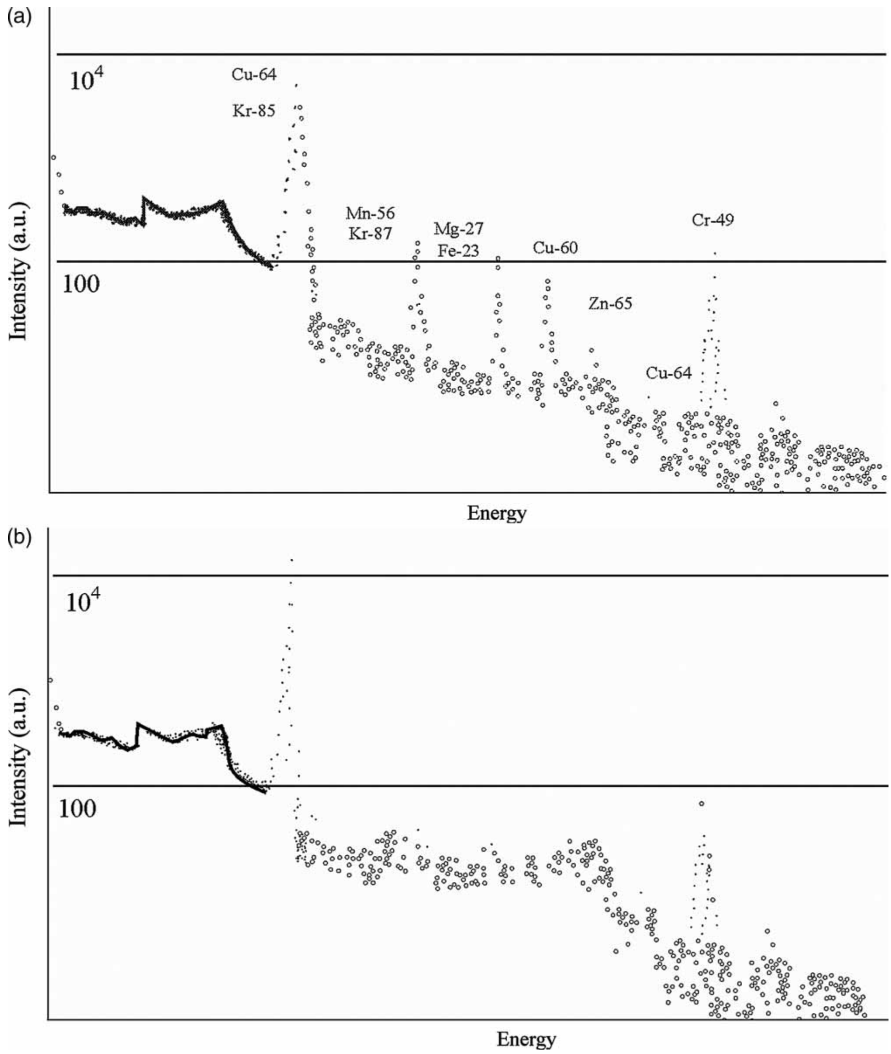

Figure 4. Diagrams of the GDT activation analyses obtained by a gamma spectrometer (a) immediately after the completion of irradiaion and (b) 6 h after the last irradiation.

the monitored propertied of TVS diodes with the increase in the absorbed dose. According to these plots, avalanche diodes exhibit a drop in turn-on voltage, the increase in the slope of the volt–ampere curve in the breakdown regime, and consequently, the decrease in the nonlinearity coefficient. For better clarity of the plots in Figure 5(b), U–I characteristics are only shown for certain values of the absorbed dose. An additional measurement of TVS diodes' performance, 10 h after the last irradiation, showed no sign of their recovery.

Changes noticed during post-irradiation inspection of TVS diodes' characteristics can be attributed to the displacement damage caused by neutron and gamma radiation. The basic radiation defect of this kind is the Frenkel pair, consisting of a displaced interstitial atom and a vacancy. Energy levels of these defects, as well as of the stable complexes which they form with atoms of impurities and dopants present in the semiconductor, are located within the energy gap. Defects that arise in the bulk of the semiconductor material of a diode may act as recombination centers. The recombination rate of minority carriers depends on the concentration of recombination centers,

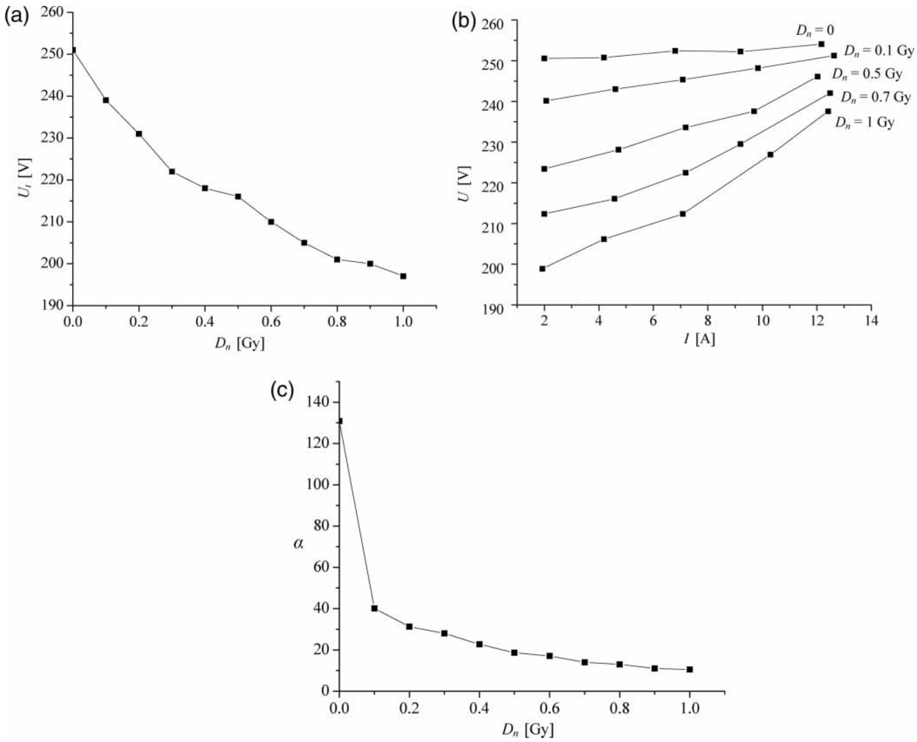

Figure 5. Dependence of TVS diode characteristics on the neutron absorbed dose in silicon: (a) the turn-on voltage, (b) U–I characteristic in the breakdown regime and (c) the nonlinearity coefficient a.

which becomes higher in an irradiated semiconductor material. The rise of the charge carrier recombination rate produces a decrease in minority carrier lifetime and mobility, which causes the semiconductor material specific resistance to diminish, ultimately resulting in the observed decrease in the TVS diode nonlinearity coefficient. In contrast, defects arising in the depletion region may act as sources of charge carrier generation, causing an increase in diode leakage current and a decrease in the avalanche diode turn-on voltage, as observed for the investigated TVS diodes (*16*).

The influence of the neutron field component on the increase in bulk carrier recombination is much larger than the influence of the gamma component, since at energies characteristic of the ^{252}Cf source neutrons cause approximately 100-fold more displacements of atoms from the crystal lattice than gamma rays can (*17*).

Lattice discontinuities at the boundary surface of the diode semiconductor material introduce surface states, with energy levels within the forbidden gap. These states act as recombination centers for charge carriers reaching the surface, in the same way as bulk defects and impurities. Areal density of such states for oxide-passivated avalanche diodes used in this paper is $\sim 10^{11}$ cm^{-2}. When semiconductor material is irradiated with gamma photons, both the surface recombination rate and the density of surface states increase (*18,19*). Increase in the surface recombination rate, as well as transient radiation effects (also called dose-rate effects, such as photocurrents produced by gamma ray ionization in the semiconductor), are manifested only during the irradiation process and therefore cause no durable damage to the diodes, which could have been observed in the conducted experiments. In view of the aforesaid, gamma-absorbed doses, which were measured during experiments, have been omitted from the paper (*20–22*).

5. Conclusion

Experimental results showed that irradiation of TVS diodes by a combined neutron/gamma field causes a lasting degradation of their protective characteristics. On the other hand, GDTs exhibit a temporary change of performance, reverting to the pre-irradiation state in a matter of hours. Some of the changes observed in the GDT, such as the speed up of its dynamic response or the lowering of the pulse breakdown voltage and its dispersion, can be regarded as an improvement of protective ability. As has been discussed in the paper, radiation-induced changes in TVS diode operation are attributed to the rise of the bulk and surface carrier recombination rates, caused by both neutrons and gamma rays. In the case of GDTs, radiation-induced changes are mainly due to the effects of the neutron field component, which ultimately lead to a higher concentration of potentially initializing free electrons in the tube's inter-electrode gap.

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