

# RELIABILITY OF SEMICONDUCTOR AND GAS-FILLED DIODES FOR OVER-VOLTAGE PROTECTION EXPOSED TO IONIZING RADIATION

by

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The wide-spread use of semiconductor and gas-filled diodes for non-linear over-voltage protection results in a variety of possible working conditions. It is therefore essential to have a thorough insight into their reliability in exploitation environments which imply exposure to ionizing radiation. The aim of this paper is to investigate the influence of irradiation on over-voltage diode characteristics by exposing the diodes to californium-252 combined neutron/gamma radiation field. The irradiation of semiconductor over-voltage diodes causes severe degradation of their protection characteristics. On the other hand, gas-filled over-voltage diodes exhibit a temporal improvement of performance. The results are presented with the accompanying theoretical interpretations of the observed changes in over-voltage diode behaviour, based on the interaction of radiation with materials constituting the diodes.

*Key words: diodes, nuclear radiation effects, over-voltage protection*

## INTRODUCTION

Over-voltage is a rather common occurrence in all electronic circuits, which makes efficient over-voltage protection a primary design requirement. The efficient over-voltage protection has two aspects: the protection of integrity (no permanent damage of the protected device) and the maintenance of operational functionality (operation reliability in the event of an over-voltage). Both power systems (energy generation, transmission

and distribution) and low-voltage (electronic) systems are susceptible to over-voltages. The extent to which an electronic component can withstand a temporary over-voltage without damage is reduced significantly as components are miniaturized [1, 2].

Over-voltage protection components can generally be divided into linear and non-linear ones. The linear group includes capacitors, coils, resistors, or their combinations as filters. Semiconductor over-voltage diodes (known also as transient voltage suppression diodes) and gas-filled over-voltage diodes (also called gas-filled surge arresters) fall into the group of non-linear over-voltage protection components. In practice, various hybrid schemes combining the linear and non-linear components are often used.

Semiconductor over-voltage diodes provide a way to increase the immunity of a circuit to electromagnetic interference (EMI) and electrostatic discharge (ESD). Most integrated circuits (IC) contain internal surge protection circuits that function well at preventing ESD failures that occur in the assembly. However, they are often inadequate for protecting against surge events that occur in the regular product usage. The surge ability of an over-voltage diode is directly related to its size, and external devices are typically ten times larger than the internal IC over-voltage

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devices. External over-voltage diodes provide a higher level of surge protection because it is not practical for an IC to incorporate large protection devices. In addition, the internal protection circuit of most IC is designed to handle only a few ESD events, while an external over-voltage device provides immunity for an indefinite amount of surges.

Gas-filled over-voltage diodes are largely used for protecting circuits in telecommunications (where 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).

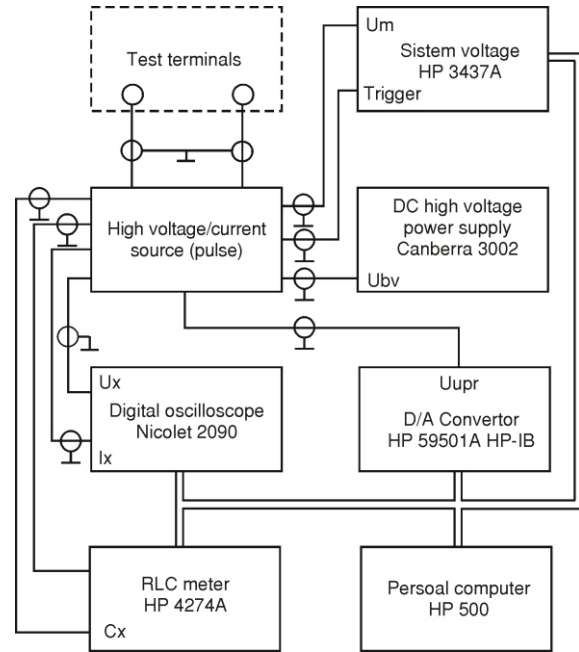
Semiconductor and gas-filled over-voltage diodes are complementary with respect to surge capability and response time. While semiconductor diodes are effective at currents up to 50 A, gas-filled diodes can withstand currents as high as 20 kA. On the other hand, semiconductor over-voltage diodes have a subnanosecond response, while the response time of gas-filled diodes can go up to 5  $\mu$ s [3, 4].

The use of modern electronic and electrical devices in conditions which imply exposure to ionizing radiation, *e. g.* at nuclear plants, in military industry and space technology, brings up the issue of over-voltage diode radiation hardness. The aim of this paper is to investigate the influence of radiation exposure on over-voltage diode characteristics. Only permanent effects, which are manifested even upon cessation of irradiation, are considered.

## THE EXPERIMENT

The measuring equipment for both semiconductor and gas-filled over-voltage diodes consisted of a current source (with a 3000 V maximum voltage), a digital oscilloscope, a DC high-voltage power supply and a personal computer. All measuring instruments were protected from electromagnetic interference by electromagnetic shielding. The experimental procedure was fully automated. This approach assured very high accuracy of measurement and good repeatability of results. The specialized PC-based control software (HP-IB or IEEE488 protocol) was developed to provide overall experiment sequencing, measurement, and data acquisition. A schematic representation of the measuring system is given in fig. 1.

The radiation induced changes of diodes' characteristics were investigated by exposing them to a combined neutron/gamma radiation field of the californium-252 source. Californium isotope  $^{252}\text{Cf}$ , encapsulated in the form of  $\text{Cf}_2\text{O}_3$ , was used. The mass of the used  $^{252}\text{Cf}$  radionuclide was 2.265  $\mu\text{g}$ , its specific neutron and gamma emission rates 2.34  $10^6 \mu\text{g}^{-1}\text{s}^{-1}$  and 5.3  $10^9 \mu\text{g}^{-1}\text{s}^{-1}$ , respectively. Average neutron energy of the  $^{252}\text{Cf}$  source is 2.14 MeV, and average gamma photon energy is 0.88 MeV.



**Figure 1. Scheme of the measuring system used for the experiments**

## Semiconductor over-voltage diodes

Commercially available avalanche silicon diodes, with 250 V nominal turn-on voltage, were used for the experiments. The diodes were all produced by a single manufacturer, with identical nominal characteristics, which resulted in low statistical dispersion of the obtained results. Each series of measurements was performed on a sample consisting of 50 diodes. Diode characteristics presented in the paper are based on the sample mean values.

The influence of ionizing radiation on semiconductor over-voltage diode operation was investigated by monitoring the volt-ampere characteristic, the volt-ohm characteristic, breakdown voltage, and the non-linearity coefficient  $\alpha$ , defined as

$$\alpha = \frac{\log \frac{I_2}{I_1}}{\log \frac{U_2}{U_1}} \quad (1)$$

where  $(U_1, I_1)$  and  $(U_2, I_2)$  are points taken from the volt-ampere curve. The experiments consisted in applying double exponential current pulses (13 A, 8/20  $\mu$ s) to the diodes and recording voltage response at the trailing edge of the current pulse, while varying the absorbed dose. Prior to each series of measurements, the over-voltage diodes were conditioned with 25 breakdowns. A thirty-second pause between each two successive measurements was introduced. The volt-ohm characteristic was calculated from the volt-ampere curve.

**Table 1. Values of neutron absorbed dose ( $D_n$ ) used for irradiation**

$n$	$D_n$ [cGy]
1	24.85
2	49.7
3	74.62

first column. The pre-irradiation state is designated by  $n = 0$ .

### Gas-filled over-voltage diodes

A commercially available argon-filled over-voltage diode, with 750 V nominal DC breakdown voltage, was used for the experiment. The radiation induced changes in the diode were examined by monitoring the DC breakdown voltage and pulse breakdown voltage random variables, as well as the pulse (volt-second) characteristic, as the absorbed dose increased. The measurement of the gas-filled diode volt-second characteristics was based on the Area law. The method consisted in applying a series of 50 double exponential voltage pulses (1.2/50  $\mu$ s) before and immediately after exposure to radiation, with a thirty-second pause between consecutive pulses.

The gas-filled over-voltage diode was subjected to three neutron absorbed doses in argon: 3.79 Gy, 6.14 Gy, and 11.17 Gy. The gamma component of the radiation field influenced the electric properties of the gas-filled diode only in the course of irradiation. Moreover, for neutron and gamma ray energies of the used  $^{252}\text{Cf}$  source, according to non-ionizing energy loss (NIEL) hypothesis, the displacement damage cross-section of the neutron component is much larger than for the corresponding gamma ray component [5-7]. These facts allowed only neutron fluence to be considered.

The influence on the DC breakdown voltage and pulse breakdown voltage random variables was tested measuring 1000 values of each. The discharge energy (current) was maintained constant during the measurement series. The results obtained in the measurement series were divided into ten groups of 50 successive values of the breakdown voltage. Thereafter, each group of the results was tested statistically. U-test with 5% significance level was used to determine whether the measurements in a single group belonged to the same random variable. Applying chi-square and Kolmogorov tests, the measured values of the breakdown voltage (within one group of measurements) were tested with respect to the type of statistical distribution (normal, exponential, double-exponential, and Weibull) [8].

The influence of radiation on the pulse characteristic was probed in the same manner, using the Area law. According to this law, there has to be a constant

The semiconductor diodes were exposed to three different levels of neutron absorbed dose in silicon ( $D_n$ ), given in tab. 1 in ascending order. Each dose level is marked by a number ( $n$ ) shown in the

geometrical area formed in the voltage-time plane between the pulse-voltage time-shape and the DC breakdown voltage level, for pulse (dynamic) breakdown to occur. Since the area delimited by pulse and DC breakdown voltages is a specific property of a particular gas, and doesn't depend on the applied voltage, knowing the size of this area suffices for the calculation of pulse (volt-second) characteristic.

## RESULTS AND DISCUSSION

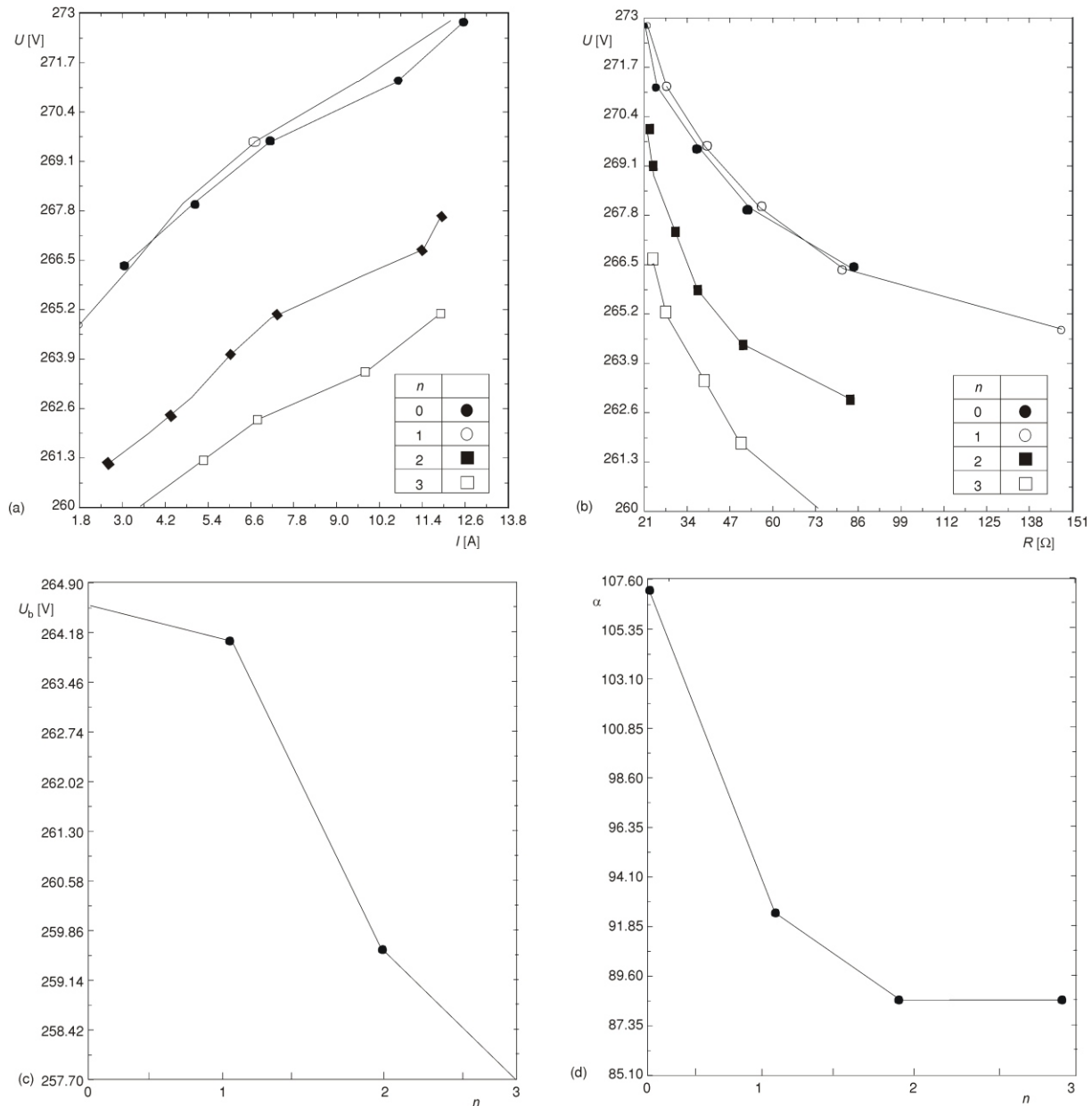
### Semiconductor over-voltage diodes

Figure 2 shows the experimentally observed changes in volt-ampere characteristic, volt-ohm characteristic, breakdown voltage, and the non-linearity coefficient of semiconductor over-voltage diodes, as the absorbed dose increases. According to these plots, the over-voltage diodes exhibit breakdown voltage drop, reflected in the increase of the volt-ampere plot slope, and consequently the decrease of the non-linearity coefficient.

Permanent changes noticed during post-irradiation inspection of semiconductor diodes' characteristics can be attributed to the so called 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. The 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. Some of these defects represent very efficient recombination centers. The recombination rate of minority carriers depends on the concentration of recombination centers, becoming higher in an irradiated semiconductor material. This further decreases minority carrier lifetime, causing an increase in diode leaking current and a decrease of the breakdown voltage. The rise of charge carrier recombination rate produces a drop in their concentration and mobility, which causes an increase of semiconductor material specific resistance. Consequently, the non-linear coefficient decreases [9, 10].

The influence of the neutron field component on the increase of bulk carrier recombination is much larger than the influence of the gamma component, since at energies characteristic of the californium-252 source neutrons cause significantly more (approximately hundredfold more) displacements of atoms from the crystal lattice than gamma rays do [11].

Lattice discontinuities at the boundary surface of 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. The areal density of such states for oxide-passivated diodes used in this paper



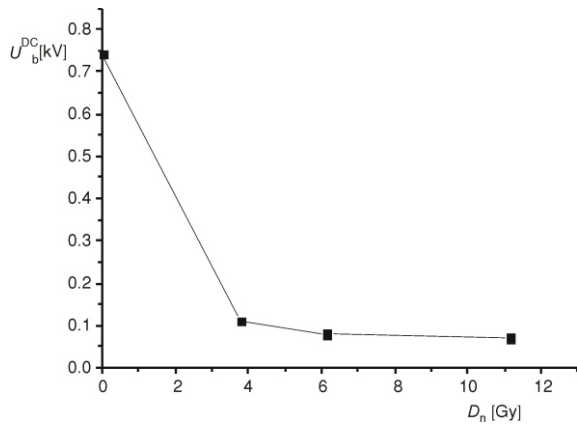
**Figure 2. Post-irradiation characteristics of semiconductor over-voltage diodes**

(a) volt-ampere characteristic; (b) volt-ohm characteristic; (c) breakdown voltage; (d) nonlinearity coefficient. Each dose level is marked by a number ( $n$ ), as shown in tab. 1. The pre-irradiation state is designated by  $n = 0$ .

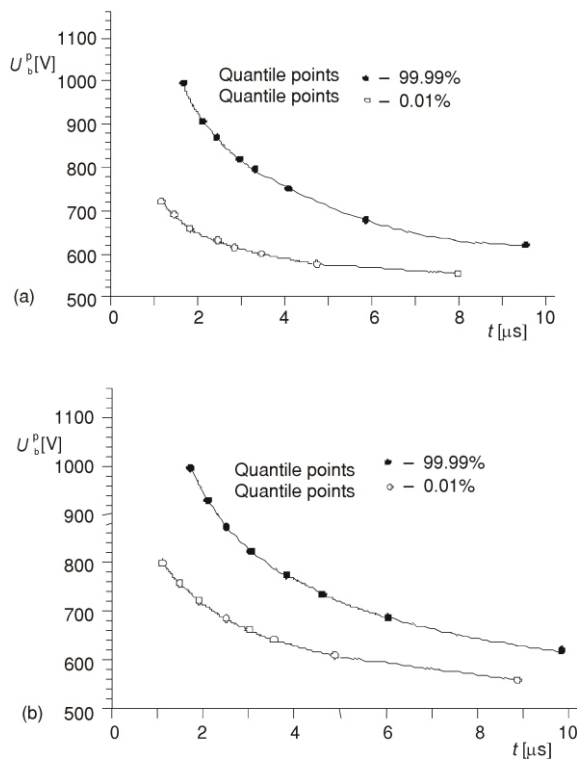
is  $\sim 10^{11} \text{ cm}^{-2}$ . When semiconductor material is irradiated with gamma photons, both the surface recombination rate and the density of surface states increase [12, 13]. The increase of the surface recombination rate, as well as transient radiation effects (also called dose-rate effects, such as photocurrents produced by gamma ray ionization in the semiconductor), is manifested only during the irradiation process, and therefore causes no permanent damage to the diodes which could have been observed in the experiments. For this reason, gamma absorbed doses, measured during the experiments, have not been stated in the paper [14-16].

### Gas-filled over-voltage diodes

Figure 3 shows the DC breakdown voltage  $U_b^{\text{DC}}$  of the gas-filled over-voltage diode vs. the absorbed dose. In fig. 4(a) and (b) the 99.99% and 0.01% quantiles of the gas-filled diode volt-second characteristic before and after irradiation are presented. The experimental results show that by irradiating the gas-filled over-voltage diode the standard deviation of its DC breakdown voltage significantly decreases (quantile curves move closer to each other). The irradiated gas-filled diode exhibited a more rapid response and had a narrower volt-second characteristic



**Figure 3. Gas-filled over-voltage diode DC breakdown voltage vs. neutron absorbed dose in argon**

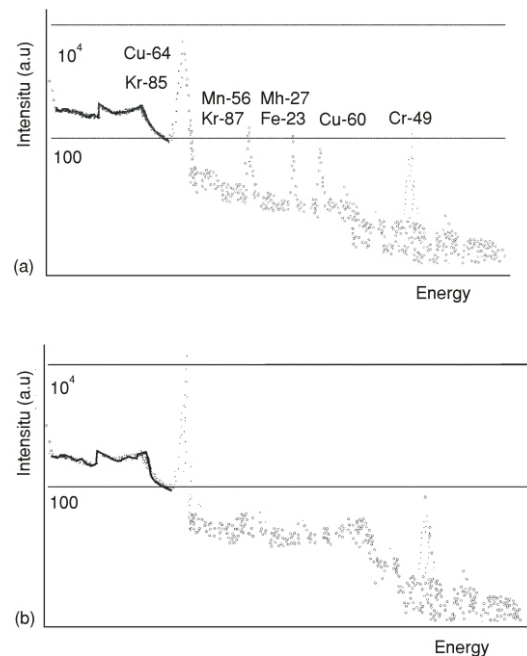


**Figure 4. Quantiles (99.99% and 0.01%) of the gas-filled over-voltage diode volt-second characteristic (a) before and (b) after irradiation**

(i. e. a smaller value of pulse breakdown voltage  $U_b^p$ ). This means that its protective characteristics were improved.

Faster response of the gas-filled diode after irradiation is a consequence of a higher concentration of free electrons in the inter-electrode gap created by gas ionization. Ionization is induced through the neutron activation of diode construction materials. The shortening of gas-filled diode response time can be attributed to higher availability of potentially initializing

free electrons. Figure 5 presents the gas-filled diode activation analysis diagrams (a) immediately after exposure to the radioactive source, and (b) six hours after irradiation, obtained by a gamma spectrometer. The activity of radioactive isotopes consists of both  $\alpha$  and  $\beta$  components. Due to the induced radioactivity, gas ionization is intensified and the statistical time of a pulse breakdown voltage is reduced. Neutron radiation effects improve the pulse shape characteristic for a short period of time. This effect of neutron radiation disappears quickly, since the half-life time of induced activity varies from several minutes to several hours. This fact is confirmed clearly by the activation analysis plot recorded six hours after irradiation, fig. 5 (b). It can be noticed from these plots that neutron activation products have decayed almost completely and that the gas-filled diode has recovered back to the pre-irradiation state [17-20].



**Figure 5. Activation analysis diagrams for the gas-filled over-voltage diode (a) immediately after irradiation, and (b) six hours after irradiation**

## CONCLUSIONS

The experimental results showed that irradiation of semiconductor over-voltage diodes by a combined neutron/gamma field causes a permanent degradation of their protection characteristics. On the other hand, gas-filled over-voltage diodes exhibit a temporal improvement of performance. As was discussed in the paper, radiation induced changes in semiconductor over-voltage diode operation is attributed to the rise of bulk and surface carrier recombination rates, caused by



both neutrons and gamma rays. In the case of gas-filled over-voltage diodes, radiation induced changes are mainly due to the effects of neutron field component, producing a higher concentration of potentially initializing free electrons in the diode inter-electrode gap.

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**Ковиљка СТАНКОВИЋ, Милош ВУЈИСИЋ, Един ДОЛИЋАНИН**

## **ПОУЗДАНОСТ ПОЛУПРОВОДНИЧКИХ И ГАСНИХ ДИОДА ЗА ПРЕНАПОНСКУ ЗАШТИТУ ИЗЛОЖЕНИХ ЈОНИЗУЈУЋЕМ ЗРАЧЕЊУ**

Широка примена полупроводничких и гасних диода за нелинеарну пренапонску заштиту доводи до различитих могућих услова рада. Због тога је неопходно имати увид у њихову поузданост у радном окружењу које подразумева излагање јонизујућем зрачењу. Циљ овог рада је да испита утицај зрачења на карактеристике пренапонске диоде, излагањем диода комбинованом неутронском и гама радијационом пољу калифорнијума-252. Озрачивање полупроводничких пренапонских диода изазива велику деградацију њихових заштитних карактеристика. С друге стране, гасне пренапонске диоде испољавају привремено побољшање карактеристика. Добијени резултати су приказани заједно са теоријском интерпретацијом уочених промена у понашању пренапонских диода, на основу интеракције зрачења са конститутивним материјалима диода.

*Кључне речи:* диоде, нуклеарни радијациони ефекти, пренапонска заштита