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Determination of a discharge channel resistance in discharges from objects with a constant charge

***Abstract**. Estimation of the energy released during a discharge from an object with a constant charge is important from the point of view of protection against static electricity. Hazards from electric discharges are one of the main factors of damage to electronic components. One of the significant parameters for determining this energy is the discharge channel resistance. The article presents the methodology for estimating the channel resistance for discharges from the capacitor surface and the dielectric fabric surface.*

***Streszczenie.** Szacowanie energii uwalnianej podczas wyładowania z obiektu ze stałym ładunkiem jest istotne z punktu widzenia ochrony przed elektrycznością statyczną. Zagrożenia od wyładowań elektrostatycznych są jednym z głównych czynników uszkodzeń elementów elektronicznych. Jednym z parametrów niezbędnych do wyznaczenia tej energii jest rezystancja kanału wyładowczego. W artykule przedstawiono metodykę oszacowania rezystancji kanałów wyładowań z powierzchni kondensatora oraz tkaniny dielektrycznej. (**Wyznaczanie rezystancji kanału wyładowczego przy wyładowaniach z obiektów ze stałym ładunkiem**).*

Keywords: discharge channel resistance, electrostatic discharge, dielectric fabrics, constant charge object.
Słowa kluczowe: rezystancja kanału wyładowczego, ESD, tkaniny dielektryczne, obiekt ze stałym ładunkiem.

Introduction

Hazards of electrostatic discharge are one of the most important factors affecting the operation of electronic devices and systems [1]. Sources of hazards may be external (e.g. lightning discharges, short-circuits) or local (e.g. overvoltage, electrostatic phenomena).

Phenomena related to static electricity constitute the largest percentage among the causes of damage to semiconductor components and integrated circuits. It was found that in 2001 about 35% of damage to integrated circuits was caused by electrostatic discharge (ESD) [2]. It should be emphasized that the energy of such a discharge can reach up to several hundred mJ, while the maximum level of energy tolerated by electronic devices often does not exceed several to several hundred μJ [3-5]. For comparison, the energy sensed by a human during a discharge from a fingertip is about 1 mJ (estimated on the basis of HBM).

Determining the maximum value of energy dissipated during an electrostatic discharge seems therefore to be a reasonable step in assessing the risk of electrostatic hazards. An important parameter enabling the determination of this energy is the discharge channel resistance. Depending on the type of discharge, the channel resistance value can be very low, i.e. several Ω (for capacitive discharge, e.g. insulated metal object) or very high, reaching values of several or even several hundred kΩ (e.g. during discharge from dielectric fabric surface). The value of this resistance is influenced by the voltage of the charged object, the length of the discharge channel and the speed of approaching the object to the electrode [6-8].

A measurement system proposal for determining the discharge channel resistance

Electrostatic discharges are discharges from objects with the so-called constant charge. A high-voltage reference capacitor was used as a model object with a constant charge. A measuring system, which allows logging the discharge current-time characteristic, has been used to determine the discharge channel resistance. The discharge channel resistance was estimated by comparing the energy stored in the capacitor with the energy released during discharge. The equivalent scheme of the measuring system is shown in Figure 1. The system contains a specially prepared reference capacitor with known capacitance C_N. A discharge electrode with and an additional resistor R_d was approached to the high-voltage capacitor electrode. The value of the resistance of the additional resistor was selected depending on the type of measurement. The discharge is marked with a switch W, while the channel resistance with an R_K resistor. The measuring system was built based on the commercially available Haefely TEST AG PESD set, which enables observation and verification of the discharge shape from the ESD generator.

The signal from the probe with a wideband shunt with an resistance of about 2 Ω controlled the oscilloscope input via the attenuator (20 dB/50 Ω). The Tektronix MSO2014 100MHz – 1 GS/s digital oscilloscope was used. For estimating the distance between the charged object and the spherical electrode at which the discharge occurred, a fast digital camera was placed near the probe, enabling the recording of images at a speed of 1000 fps.

To cause a discharge, the charged capacitor or sample was approached to a spherical electrode with a radius of r_0 = 7.5 mm compliant with EN-13463-1standard.

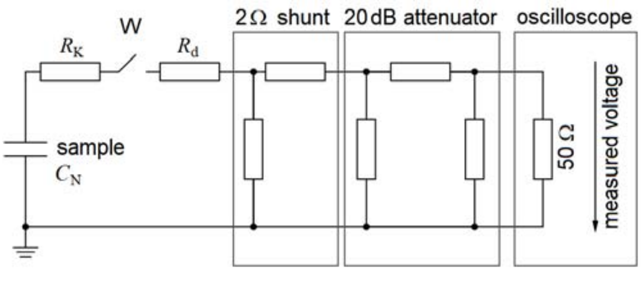

Fig. 1. The equivalent scheme of the measuring system for logging the discharge current-time characteristic during sample discharge, W – switch representing the occurrence of discharge (when closed)

Verification of the method of determining channel resistance: reference capacitor

In order to verify the propriety of measurements performed on the presented system, a reference capacitor was prepared. The capacitor model is shown in Figure 2. The dimensions of the capacitor have been specified to provide a capacitance of about 10 pF. This value is comparable with the capacitance of tested dielectric fabric sample. The total measured capacitance was C_N = (14.5±0.5) pF in the experiments.

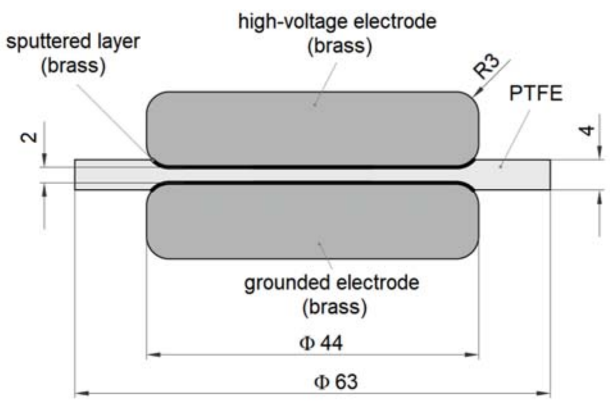

Fig. 2. Model of the reference capacitor

A voltage of $U_0 = 5$ kV with positive polarity was applied to the high-voltage electrode. The other electrode was grounded. The entire capacitor, from the side of the high-voltage electrode, was approached to a spherical electrode (with an attached probe) to start a discharge. As an additional resistor a low-induction resistor with a value $R_d \cong 920\ \Omega$ was used. The value of R_d was set to avoid damped vibrations. The whole process, i.e. approaching the capacitor to the spherical electrode and electrical discharge was recorded with a fast camera. An example of the observed spark-over is shown in Figure 3.

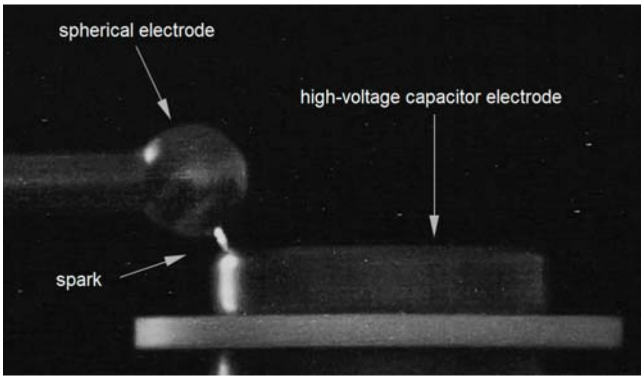

Fig. 3. Electrical discharge (i.e. spark discharge) from a surface of high-voltage reference capacitor electrode

The discharge current waveform was logged with an oscilloscope in the form of a voltage drop across the probe resistance over the time. The voltage-time characteristic was then converted to the current-time characteristic $i = f(t)$ (see Figure 4).

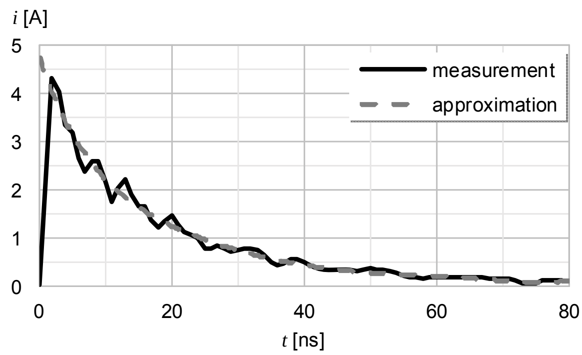

Fig. 4. Current-time characteristic of discharge from a surface of high-voltage reference capacitor electrode

The system verification consisted in comparing the energy released during the discharge W_1 with the energy stored in the capacitor W_2. The energy W_1 was estimated from the obtained characteristic $i(t)$ and given by:

$$W_1 = R_T \int_0^{t_{ESD}} i^2(t)\,dt\ , \tag{1}$$

where: t_{ESD} – capacitor discharging time, $t_{ESD} \cong 80$ ns, R_T – equivalent total resistance:

$$R_T = R_d + R_K\ , \tag{2}$$

where R_K is the discharge channel resistance.

The energy W_2 was determined from:

$$W = \frac{1}{2} C U^2 . \tag{3}$$

The capacitance C was expressed as:

$$C = C_N + C_S\ , \tag{4}$$

where: C_N – capacitance of the sample (here: reference capacitor), C_S – capacitance between the spherical electrode and the sample (here: high-voltage electrode of the reference capacitor).

The voltage U was equal to:

$$U = U'\ , \tag{5}$$

where: U' – voltage at high-voltage electrode (reduced due to the inclusion of C_S capacitance), given by equation:

$$U' = U_{p0} \frac{C_N}{C_N + C_S}\ , \tag{6}$$

where: U_{p0} – actual voltage at the high-voltage electrode, taking into account the time of the charge decay from the moment of charging the capacitor (to U_0 voltage) to the occurrence of the discharge. The U_{p0} value was determined from the voltage-decay characteristic.

Finally, the energy W_2 is given by:

$$W_2 = \frac{1}{2} \frac{C_N^2}{C_N + C_S} U_p^2 . \tag{7}$$

For a spherical electrode with radius of $r_0 = 7.5$ mm and a distance $h = 4$ mm (distance between the high-voltage electrode and the spherical electrode at the time of the discharge occurrence), the C_S capacitance is $C_S \cong 1.05$ pF (determined numerically based of finite element simulations). The U_{p0} voltage value, determined on the basis of the voltage-decay characteristic $U_p = f(t)$ is $U_{p0} \cong (4.90 \pm 0.05)$ kV (see Figure 5). The values of both energies W_1 and W_2, determined from equations (1) and (7) are equal to (155±3) μJ and (150±3) μJ, respectively. The similarity of obtained energy values indicates the propriety of the used methodology.

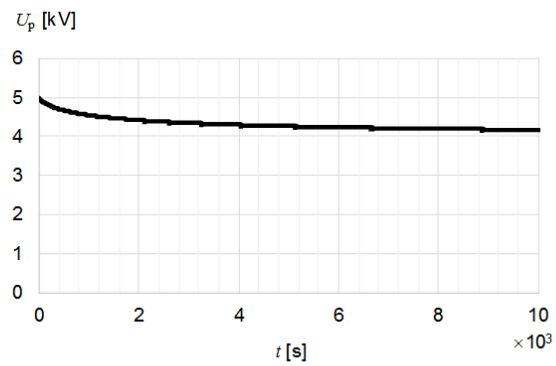

Fig. 5. Voltage-decay characteristic for reference capacitor

Determination of the discharge channel resistance value for a reference capacitor

The value of the equivalent resistance of the discharge channel was estimated based on the analysis of the initial value of the discharge current. The maximum current value I_{max} occurs for time t = 0 s, meaning the moment of discharge. Due to the finite start time of the oscilloscope time base (by the discharge current pulse) and the rise time of the input amplifier, the value I_{max} of the discharge current was determined by extrapolation for t = 0 s based on the approximation of characteristic $i = f(t)$ by 6th degree polynomial. The value of I_{max} is determined by:

$$I_{max} = \frac{U'}{R_T}, \tag{8}$$

where resistance R_T is described by equation (2). Thus, after elementary transformations, the channel resistance R_K is given by:

$$R_K = \frac{U_p C_N}{I_{max}(C_N + C_S)} - R_d. \tag{9}$$

The value of I_{max} determined on the basis of approximation of characteristic shown in Figure 4 is equal to $I_{max} \cong$ 4,75 A, which in combination with (9) leads to the value of the discharge channel resistance equal to $R_K \cong$ (45±5) Ω.

Channel resistance at discharge from the surface of a dielectric

Electrified fabric is the source of the electric field. This electric field can store energy the release of which is the cause of discharges [9]. In a case of a discharge from the surface of a dielectric object (i.e. dielectric fabric) it should be expected that the resistance of the discharge channel will be many times higher than for an insulated conductive object (reference capacitor).

An attempt to estimate the equivalent resistance of the R_K discharge channel during ESD from the surface of a charged dielectric was carried out for a dielectric fabric made of polypropylene. The fabric was washed in an ultrasonic cleaner. Discharge current measurements were made for a sample with a diameter of Φ = 50 mm and a thickness d = 0,6 mm. The sample of the fabric was not antistatic, i.e. it did not have any conductive fibres woven into its structure. The sample was electrified with corona discharge. The electrification was carried out in accordance with [10] under the following conditions: corona voltage U_u = +10 kV, corona discharge time t_u = 30 s. During measurement of the discharge current over time, the sample was kept upright with a grounded metal tweezer.

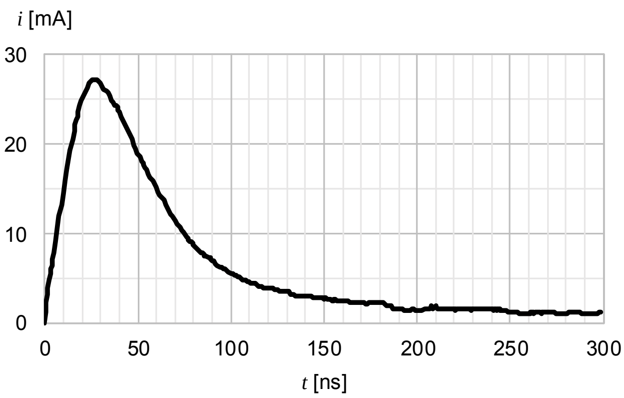

Fig. 6. Current-time characteristic during an ESD discharge from a charged dielectric fabric surface, $R_d \cong$ 11 kΩ

The current-time characteristic for the discharge between the fabric sample surface and the spherical electrode is shown in Figure 6. The result is similar to that obtained for a reference capacitor.

The $i = f(t)$ characteristics were made for various values of the additional resistor R_d: 1 kΩ, 5 kΩ, 11 kΩ, 100 kΩ and without it, where R_d value was assumed to be 2 Ω (shunt resistance). Five measurement tests were performed for each additional resistance value.

Based on the measurements, the $I_{max\ avg} = f(R_d)$ characteristic was plotted. It allowed to determine R_d resistance value for which $I_{max\ avg}$ current value begins to decrease. This phenomenon occurs when R_d and R_K resistances have similar values. The $I_{max\ avg} = f(R_d)$ characteristic for the case of discharge from the surface of a dielectric fabric is shown Figure 7. If it is assumed that the value of $I_{max\ avg}$ for $R_d \cong R_K$ decreases to the level of ½ (compared to the value of $I_{max\ avg}$ as for $R_d << R_K$) the results presented in Figure 7 indicate that the R_K is equal to (1-2)×10^5 Ω.

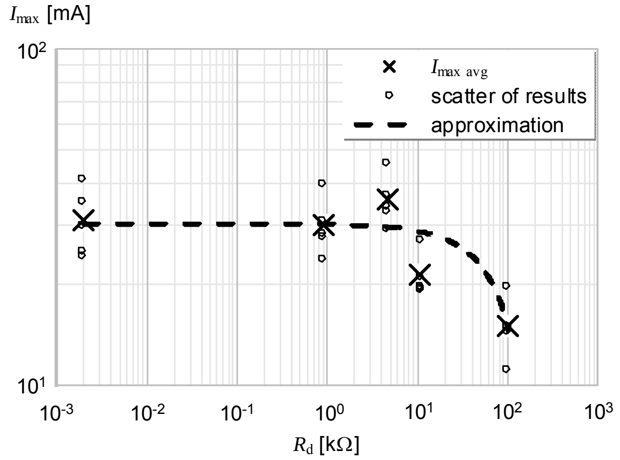

Fig. 7. Dependence of the maximum current value $I_{max\ avg}$ on the additional resistance R_d

In the case of a discharge from the dielectric surface, a significant difficulty in using the equation (9) is mainly associated with the determination of the capacitance C_N and voltage U'. An important parameter determining the values of both of the above-mentioned variables (C_N and U'), as well as necessary for the simulation estimation of the value of C_S, is the distance h between the spherical electrode and the dielectric fabric at which the ESD occurs. The h parameter for the discharge from the fabric surface was determined on the basis of the analysis of images obtained from the camera. It was estimated as $h \cong$ (7.5±0.2) mm. The value of h allows to estimate the initial voltage U' based on the electrical strength of air. Assuming its value for the estimated h distance as E_{kr} = 3×10^6 V/m [11] and with the maximum discharge current 30 mA, the initial voltage U' and discharge channel resistance R_K values were obtained, as equal to U' = 22.5 kV and $R_K \cong$ 7.5×10^5 Ω, respectively. The results of both estimation methods, neglecting the large discrepancy, indicate much higher values of discharge channel resistance in the case of discharges from the surface of dielectric objects as compared to that for the discharge from conductive object (reference capacitor electrode).

Based on the $i = f(t)$ characteristics and assuming that the channel resistance is equal to $R_K \cong$ (2.0-7.5)×10^5 Ω, it was estimated from equation (1), that the value of energy released during ESD is in the range of 5.5-20.5 μJ.

Conclusions

The experimental tests were aimed at estimating the equivalent resistance of the discharge channel for discharges from objects with a constant charge. The channel resistance is an important parameter for determining the energy released during a discharge, which allows determining the probability of hazards (electronics damage, ignition of a combustible medium). The so-called "flammability" depends not only on the value of the discharge energy, but also on the discharge power. If the same energy is lost in a long time, the discharge power will be insufficient to ignite.

The method of determining the discharge channel resistance was verified based on measurements of spark discharges from the surface of a high-voltage electrode of a specially prepared reference capacitor with a capacitance of (14.5±0.5) pF. It was found that for this type of object the method is correct, i.e. the determined value of the discharge channel resistance (not exceeding several dozen Ω) is reliable and similar to the values given in the literature [6-8]. The estimated energy released during the discharge was approximately equal to the energy calculated from the general dependence on the energy stored in the capacitor (6.5% difference). The difference between the determined energy values can be caused by the accuracy of the assumed t_{ESD} discharge time and U' voltage value, as well as by omitting the emission of light, acoustic energy and electromagnetic radiation.

The determined discharge channel resistance for dielectric fabrics is many times higher than the resistance for insulated metal objects. Considering that the duration of electrostatic discharge is very short (10^{-9}-10^{-6} s), and the resistance of the discharge channel of dielectric materials is very high ($R_K \cong (1\text{-}2)\times10^5\ \Omega$), one should expect discharges with high power, which may result in damage to electronic devices or ignition of explosive atmospheres.

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