Influence of Electrodes Configuration on Metallized Film Capacitor Performance Metrics

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Abstract. The aim of the study is to reveal the influence of the electrode configuration of metallized film capacitors on their characteristics and performance under conditions typical of power electronics. Presently used electrodes configurations are summarized, their benefits and disadvantages are analyzed. We showed that currently used metallized film capacitors electrodes configurations, ensuring reliable self-heling, have too high equivalent resistivity. Authors propose to introduce a hybrid type of electrode for metallized film capacitors. We showed the influence of the capacitor electrodes on its performance under the conditions typical of power electronics and experimentally studied the effect of the electrode thickness on the breakdown strength. The breakdown strength of polymer films with various metallization thickness was determined using common dielectric testing methodology. We found out that the breakdown strength follows Weibull distribution and slightly depends on vacuum sputtered metal thickness, unlike previous studies results. The effects from the fracture of electrodes caused by electrical discharges occurring during self-healing of metallized film capacitors are demonstrated experimentally. It was established the prominent influence of electrical explosion and micro-arc destruction of metallized electrode on polymer film breakdown strength. The results of numerical and analytical calculations of equivalent electrode resistivity for various configurations are presented. Comparative calculations of the surface resistance and active area of segmented and hybrid electrodes showed the advantage of the latter. We experimentally established that at comparable process durations the deposited energy for the fracture of hybrid electrodes was less than for segmented ones.

***Keywords*:** metallized film capacitor, breakdown strength, electrode configuration, equivalent series resistance, self-healing, profile metallization, segmented metallization.
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Influența configurației electrozilor asupra parametrilor de performanță a condensatorului cu film metalizat

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Abstract. Scopul studiului este de a releva influența configurației electrozilor condensatoarelor cu peliculă metalizată asupra caracteristicilor și performanței acestora în condiții tipice electronicii de putere. Sunt rezumate configurațiile electrozilor utilizați în prezent, sunt analizate beneficiile și dezavantajele acestora. Am arătat că configurațiile electrozilor de condensatoare cu peliculă metalizată utilizate în prezent, care asigură auto-heling fiabil, au o rezistivitate echivalentă prea mare. Autorii propun introducerea unui tip hibrid de electrod pentru condensatoare cu film metalizat. Am arătat influența electrozilor condensatorului asupra performanței acestuia în condițiile tipice electronicii de putere și am studiat experimental efectul grosimii electrodului asupra rezistenței la defalcare. Rezistența la rupere a filmelor polimerice cu grosimi diferite de metalizare a fost determinată utilizând metodologia comună de testare dielectrică. Am descoperit că rezistența la rupere urmează distribuția Weibull și depinde ușor de grosimea metalului pulverizat în vid, spre deosebire de rezultatele studiilor anterioare. Efectele ruperii electrozilor cauzate de descărcările electrice care apar în timpul autovindecării condensatoarelor cu peliculă metalizată sunt demonstrate experimental. Sa stabilit influența proeminentă a exploziei electrice și a distrugerii micro-arcului electrodului metalizat asupra rezistenței la rupere a filmului polimeric. Sunt prezentate rezultatele calculelor numerice și analitice ale rezistivității electrodului echivalent pentru diverse configurații. Calculele comparative ale rezistenței suprafeței și ariei active a electrozilor segmentați și hibrizi au arătat avantajul acestora din urmă. Am stabilit experimental că la durate de proces comparabile energia depusă pentru ruperea electrozilor hibrizi a fost mai mică decât pentru cei segmentați.

***Cuvinte-cheie*:** condensator cu peliculă metalizată, rezistență la rupere, configurație electrod, rezistență serie echivalentă, auto-vindecare, metalizare profil, metalizare segmentată.

Влияние конфигурации электродов на работоспособность металлопленочных конденсаторов

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Аннотация. Целью исследования является выявление влияния конфигурации электродов металлопленочных конденсаторов на их характеристики и работоспособность в условиях, характерных для силовой электроники. Обобщены литературные данные об используемых в настоящее время конфигурациях электродов, проведен критический анализ их преимуществ и недостатков. Показано, что используемые в настоящее время конфигурации электродов металлизированных пленочных конденсаторов, обеспечивающие удовлетворительное самовосстановление конденсатора, имеют слишком высокое эквивалентное сопротивление. Предложена конфигурация электрода для металлопленочных конденсаторов, сочетающая в себе преимущества сплошного и сегментированного электродов, называемая гибридным электродом, а также получены экспериментальные образцы гибридных электродов. Продемонстрированы различные аспекты влияния электродов конденсатора на его работоспособность, экспериментально изучено влияние толщины электрода на электрическую прочность. Электрическая прочность полимерных пленок с различной толщиной металлизации была определена с использованием стандартных методик испытаний диэлектриков. Обнаружено, что электрическая прочность подчиняется распределению Вейбулла и незначительно снижается от толщины вакуумно-напыленного металла, в отличие от результатов исследований, представленных в литературных источниках. Экспериментально исследовано разрушение электродов, вызванное электрическими разрядами, возникающими при самовосстановлении металлопленочных конденсаторов. Установлено, что электрический взрыв и микродуговое разрушение металлизированного электрода существенно влияет на электрическую прочность полимерной пленки. Представлены результаты численного и аналитического расчетов эквивалентного поверхностного сопротивления для различных конфигураций электродов. Сравнительный анализ поверхностного сопротивления и активной площади сегментированных и гибридных электродов показал преимущество последних. Экспериментально установлено, что при сравнимой длительности процесса самовосстановления затрачиваемая на разрушение гибридных электродов энергия была меньше, нежели у сегментированных. Тем самым продемонстрирована способность гибридных электродов обеспечивать удовлетворительное самовосстановление металлопленочного конденсатора при меньшем эквивалентном сопротивлении электрода, чем у профильной и сегментированной металлизации.

Ключевые слова: металлизированный пленочный конденсатор, пробивная прочность, конфигурация электродов, эквивалентное последовательное сопротивление, самовосстановление, профильная металлизация, сегментная металлизация.

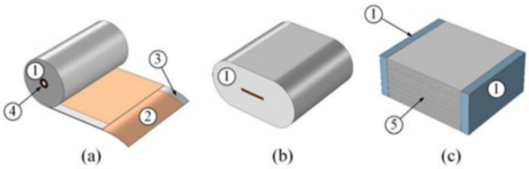
INTRODUCTION

Capacitors are one of the key components in power electronics systems in terms of reliability, weight and size characteristics, volume and cost efficiency [1]. They are extensively used in power and frequency converters. A wide range of power electronics applications, such as wind generators, photovoltaic systems, electric vehicles [2], variable frequency control of electric drive [3] and HVDC power lines [4,5] implies using of those converters.

At the moment there is a growing trend of more widespread use of metallized film capacitors (MFC) in power electronics. MFCs are known due to self-healing (SH) ability which is the capacitor's performance recover after local dielectric breakdown [6]. MFCs are one of the types of the organic dielectric capacitors and have been used in power electronics since the 90s of last century [7,8]. Nevertheless, only in the last decade they have managed to firmly occupy the leadership among other types of capacitors. MFCs are superior to ceramic and electrolytic capacitors in high-voltage systems and power converters with high ripple currents in such characteristics as loss tangent, equivalent series resistance (ESR), capacitance stability, cost and reliability [2, 9]. Significant advantage of MFC is an unsurpassed flexibility of production technology which allows to manufacture products not only of standard designs shown in the Fig. 1, yet also to widely modify their design for the customer, creating non-standard designs in the form of toroids, coaxially nested cylinders, etc. [10]. Fig. 2 illustrates the principle of MFCs SH in the case of all-over electrode type: after dielectric breakdown occurs the capacitor's opposite electrodes become short circuited by breakdown channel and a large current flows. Because of small thickness of the electrode the high current density around the breakdown channel causes partly evaporation of the electrode and isolation of the breakdown area from the undamaged electrode. SH is typically followed by small capacitance decrease, corresponding to electrode area of units-tens of square mm.

MFCs are used in power electronics in many ways: as EMI-filters [11], AC and DC filters, snubbers, output filters, resonant capacitors, DC-links [12]. DC-link capacitors reliability is especially important topic because of widespread use of pulse-width converters [13]. Due to the increasingly strict reliability requirements imposed by the automotive, aerospace and energy industries, the design of DC links is associated with the following issues:

1. Capacitors are one of the main causes of failure of power electronic systems operating in the field [14];
2. Capacitors are exposed to harsher conditions (e.g. high ambient temperature, high humidity, etc.) in new applications [15, 16];
3. Trends in the development of power electronic systems with high specific power impose restrictions on the capacitors' volume and heat dissipation.



(a) cylindrical capacitance element, (b) flat-pressed capacitance element, (c) film chip-capacitor. 1 – sprayed end, 2 – metallization, 3 – non-metallized edge, 4 – mandrel, 5 – layers of metallized polymer film [17].

Fig. 1. Typical metallized film capacitors designs.

In connection with the aforesaid, it can be concluded that MFCs in power electronic systems are exploiting practically at the limit of their capabilities in terms of maximum operating temperature and rated voltage. Herewith, their reliability, although being ensured by the SH ability, nevertheless leads to accelerated decrease of capacitance due to frequent occasions of SH. The latter causes a decrease in the efficiency and reliability of the power converters themselves. Ceramic capacitors based on various ferroelectric and antiferroelectric compositions [18] with higher specific volumetric energy and capacitance could be an alternative to MFCs. However, their intrinsic dependence of capacitance on voltage, reduced reliability due to the absence of the SH, as well as the high price associated with the global shortage of rare earth metals [19] essential for ceramic compositions, make their advantages at least controversial. Due to the rapid development of electric transport worldwide, the problem of improvement the reliability of MFCs as crucial components of power converters becomes extremely relevant.

At present the work is being carried out in two general directions to solve aforementioned issues. Firstly, the improvement of dielectric characteristics of applied and the introduction of new polymer capacitor films. It is known that polypropylene (PP) currently occupies a dominant position among the polymer capacitor films used [20]. This is due to its processability, thermal stability and high dielectric characteristics. Extremely low thickness (~1 µm) and dielectric loss (~10-4), as well as high dielectric strength (700-800 kV/mm) of PP films allowed MFCs to surpass the performance of electrolytic capacitors, previously widely used in power electronics, in terms of specific capacitance, ESR, permissible ripple current magnitude. The advantages of MFCs also include insensitivity to voltage polarity and the reliable operation at high voltages. The disadvantages of PP are low dielectric constant, as well as a limited operating temperature range up to 105 °C. In this regard, the research is underway on the development and implementation of high-temperature polymer dielectrics with an increased permeability value [21-23].

Still, the high dielectric loss of such materials, the possible reduction of SH ability, the limited volume of production even of laboratory samples, coupled with the high price, make the prospect of introducing new capacitor films very remote.

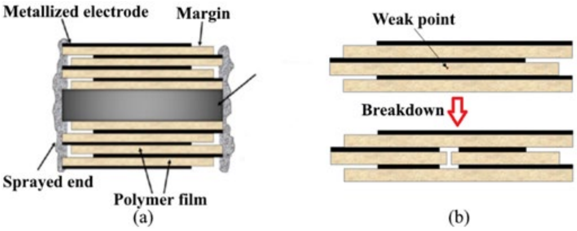


Fig. 2. Cross-section of cylindrical capacitance element (a) and explanation of self-healing principle (b).

The second approach to improving the characteristics of MFC is the study and improvement of electrode systems, including capacitor electrodes, sprayed end, contact nodes, and terminals. The literature analysis and the authors' own experience show, that the capacitor electrode configuration affects (in certain cases significantly) the following characteristics of both polymer films and capacitor in general: dielectric strength of film [24,25], specific capacitance [26], ESR [27,28], self-healing process efficiency [29-31], capacitance stability due to corrosion processes [32,33], etc.

This article presents the results of study of the electrode configuration influence on the characteristics of capacitors and development of approach to the optimal choice of MFC electrodes parameters in order to increase their efficiency in various fields of application.

I. METALLIZED FILM CAPACITORS ELECTRODES CONFIGURATIONS

We consider a part of the electrode system directly adjacent to the dielectric - the capacitor electrodes. MFC electrodes are thin layers of vacuum-deposited metal on a polymer film. As the deposited metal act mainly relatively low-melting metals, such as zinc and aluminum. It is important to emphasize that the resistivity of conductors with submicron layer thickness is higher than that of bulk ones and inversely proportional to their thickness (so called size effect) [34].

Depending on the distribution of the metal layer over the dielectric, capacitor electrodes are divided into all-over, covering the entire surface of the dielectric on one or both sides except for the margin, and segmented, consisting of many elements connected by small gates, called segments (see Fig. 3 and Fig. 4b). The area of the segments can be different, and the segments themselves most often have the shape of regular polygons: squares (rhombi), triangles, parallelograms, hexagons, etc. More complex shapes, such as spindle-shaped segments, are also technologically possible [35]. The introduction of fusible gates improves the SH process by limiting the duration of current through the breakdown channel and quickly isolating the damaged electrode segment from the rest of the capacitor electrode by destroying narrow fusible gates (see Fig. 3). The advantage of using segmented metallization is to enhance the reliability of MFC by limiting the energy amount released during SH. Nevertheless, there is a challenging issue to develop an optimum capacitor's electrode design which would not trigger the destruction of all gates of a segment to interrupt the current due to comparatively small SH acts [36]. Besides, there are such disadvantages of segmented metallization as incomplete cover of the dielectric area with an electrode, high electrode resistance, vulnerability to electrochemical corrosion due to the large electrode edges length with increased electric field strength. In addition, at current loads typical for pulsed power, energy storage and power electronics applications, there is a possibility of gradual destruction of fusible gates by an electrothermal mechanism due to the increased current density through the gate [34], even at rated current value, which leads to faster capacitance decrease and negatively affects the reliability of MFC [37].

According to the variation of the metal layer thickness, there are electrodes with uniform thickness and with thickness varied along the width of the polymer film, called profile metallization. In turn, the profile metallization could have a thickness that varies smoothly according to a linear or power law, or that one changes sharply, stepwise. The application of profile metallization makes possible to significantly increase the resistance of the electrode and thus limit the current and energy of the SH, alongside that ensuring reliable contact of the electrode with the sprayed end due to the increased thickness of one of the electrode edges. In the case of uniform metallization, it is also possible to use ultrathin metallization of polymer film with a layer of aluminum or zinc with a thickness of 2-5 nm [24,25]. The advantages of this type of electrode are full cover of dielectric area with electrode and the effective SH due to the rapid extinction of the micro-arc discharge caused by very high resistance of the electrode. Moreover, the application of an ultrathin metallization allows to reduce the duration of external action on the polymer film and minimize the negative effect of the metallization process on formation of weak points and imperfections of dielectric. However, besides the obviously high resistivity, the disadvantage of ultrathin metallization is the greater vulnerability of the capacitor contact node, since the contact resistance between sprayed end and electrode increases as the thickness of the latter decreases.

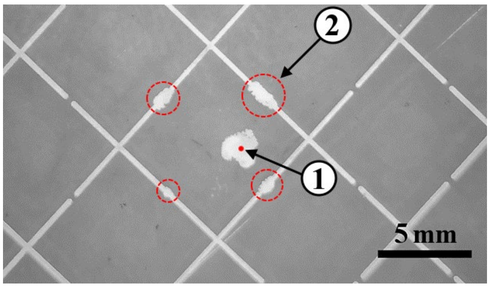


Fig. 3. Photograph of breakdown puncture in segmented metallized film with one segment cut-off. 1 – breakdown puncture with a demetallization zone around, 2 – burnt out fuses.

A. The concept of hybrid type of metallized electrodes

The main disadvantage of all the electrode configurations described above is the high resistance, which is crucial for PP-based MFCs, since the electrode loss becomes significant and comparable to that one in the dielectric in ripple current modes, typical for capacitors in power electronics.

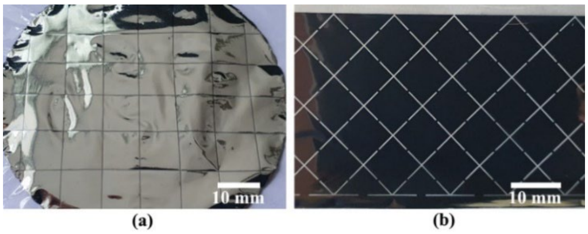


Fig. 4. Photographs of metallized polymer films with patterned metallization: (a) a hybrid type of metallization developed by the authors; (b) an industrial grade polymer film with segmented metallization.

In order to eliminate this disadvantage, the authors developed a type of electrode of an original design (you can find photograph in Fig. 4a and drawing in Fig. 5) that combines the key features of all-over and segmented electrodes. The main idea is as follows: thick segmented metallization consisting of elements with low surface resistivity, provides a reduced electrode resistance, and thin all-over metallization deposited over it, being an element with higher surface resistivity, performs the function of fusible gates as in traditional segmented metallization. The isolation of the damaged segment is ensured by breaking the contact between two metallization layers of different thickness due to the increased current density in the contact zone. The authors propose to call such electrode configuration a hybrid type of electrode or hybrid metallization. It should be noted that previously attempts have been made [38] to combine all-over and segmented metallization, and thus merge the advantages of both types of electrodes, yet authors did not manage to find any information about physical implementation of such designs or about their comprehensive studies.

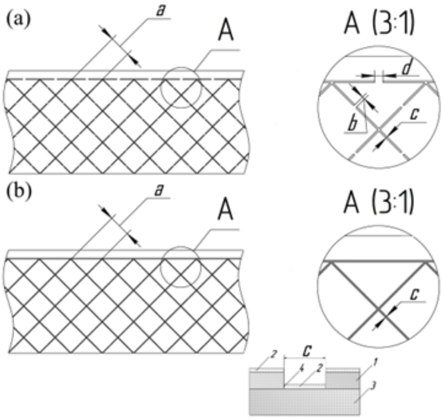


Fig. 5. Drawings of segmented (a) and hybrid (b) electrodes: a, b, c, d are widths of segment, fuse between the segments, inter–segment gap, heavy edge fuse, respectively; 1 – thick metal layer, 2 – thin metal layer, 3 – polymer film, 4 – contact zone between elements.

II. THE EFFECTS OF ELECTRODES INFLUENCE

A. The effect of electrode thickness on breakdown strength

Metallized polymer dielectrics for MFCs are manufactured using two techniques: vacuum-thermal and magnetron sputtering. It is important to note that the electro- and thermophysical properties of a thin metal film electrode are highly dependent on its thickness. In addition, the process of depositing an electrode on a polymer film also affects the properties of the capacitor dielectric itself. A thicker applied metal layer results in a longer and more intense thermal effect of the deposited metal on the film, especially on its surface layers. Greater thickness clearly ensures lower electrode surface resistance, which has a positive effect on a capacitor's ESR, and hence its losses. On the other side, it is known that the lower the electrode resistance, the more energy is dissipated around the breakdown area in the SH process [39]. This increases the probability of catastrophic capacitor failure. In addition, another negative consequence of high electrode thickness could be a reduction of polymer film dielectric strength.

Limited information on the effect of metallization thickness on the dielectric strength of polypropylene films can be found in the literature [24,25]. The dependence of dielectric strength E_{br} on metal layer surface resistivity ρ_s according mentioned sources could be expressed as

$$E_{\text{br}}(\rho_s) = E_{\text{br}\infty} + \frac{E_{\text{br}0} - E_{\text{br}\infty}}{1 + \left(\rho_s / \rho_{s0}\right)^k},$$

where $E_{\text{br}\infty}$ and $E_{\text{br}0}$ are dielectric strength by very high and very low surface resistivities, correspondingly, ρ_{s0} and k are experimental parameters depending on dielectric type, metallization technique etc.

Aforementioned studies show that applying a metal layer of 20 to 50 nanometers thick can reduce dielectric strength by 50 percent and even more. However, such a significant reduction in dielectric strength seems questionable because these sources do not provide data from direct experiments. To investigate this issue, the authors performed the following experiments. Aluminum layers of different thicknesses (10, 20, 50 nm) were deposited to 8 μm thick polypropylene film using a vacuum-thermal sputtering method, and then the dielectric strength of the original film and the films with the applied metallic layers were compared. In addition, an aqueous potassium hydroxide solution was used to obtain a sample of chemically demetallized film from a sample with 50 nm thick metal layer. The purpose of this experiment was to evaluate the influence of metal layer thickness on the dielectric strength. Weibull distributions of polypropylene films dielectric strength with different metallization thicknesses are shown in Fig. 6. The lines in the figure are marked according to the Al layer thickness. Since the results for 10 nm and 20 nm thickness were not significantly different, only the data for 20 nm metallization were added to the graph. The results are presented on a united graph for comparison. All data presented have been normalized to 63% percentile dielectric strength value (490 V/μm) of the original nonmetallized polypropylene film for ease of comparison. As shown in Fig. 6, depositing a metal layer on the surface of the polymer film does slightly affect the dielectric strength, unlike before mentioned studies results.

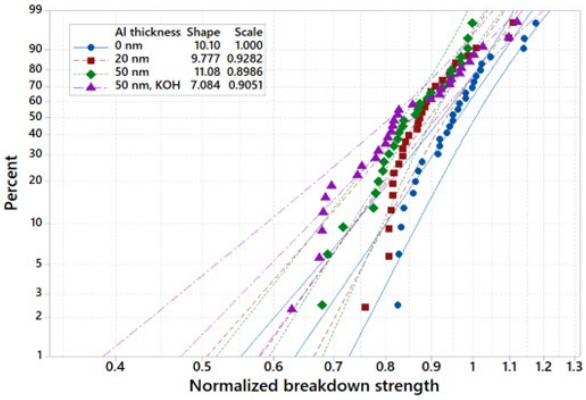


Fig. 6. Influence of metallization thickness on breakdown strength of polymer film.

There is a decrease in the dielectric strength of the metallized film ranging from 7% for 10 and 20 nm films to 10% for a 50 nm electrode. Areas under a thicker electrode have lower dielectric strength compared to areas under a thinner metal layer. Thus, thinner electrodes have a positive effect on both the SH energy dissipation and the dielectric strength of the capacitor film.

B. The effect of the discharge phenomena on breakdown strength

In addition to affecting the breakdown strength of an original polymer film due to their thickness, electrodes can cause a negative effect on the polymer properties during the SH process. It is known that the SH process consists of several stages, including the electrical explosion of minor electrode area near breakdown channel and a micro-arc discharge that ensures the burnout of larger area of the electrodes around the breakdown location [40].

A comparative study was conducted to determine the effect of the polymer film demetallization technique on its electrical strength [41,42]. For this purpose, the breakdown strength of an original metallized capacitor grade PP film and that one of the same demetallized film was studied. The demetallization techniques were as follows: chemical (by means of KOH water solution), micro-arcing, electrical explosion.

The results of the study are shown in Fig. 7. The values were normalized to 63% percentile breakdown strength value of original metallized polypropylene film in order to make the data easier to compare. This value is 620 V/μm for the Al metallized film and 530 V/μm for the Zn metallized film. As can be seen, the breakdown strength of the films remains at almost the same level after the metallization is chemically removed. This fact allows us to exclude from consideration the effect of metallization roughness and local electric field enhancement on breakdown strength.

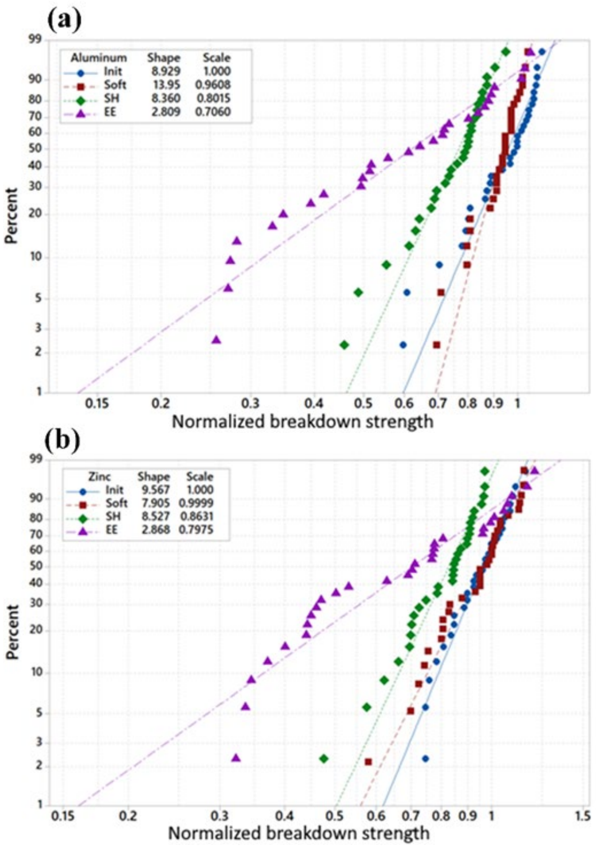


Fig. 7. Weibull distributions of breakdown. strength of demetallized polymer films: Init – initial metallized film, Soft – chemical demetallization, SH – demetallization by microarc discharge, EE – demetallized by electric explosion. (a) – aluminum, (b) – zinc.

Demetallization by means of electrical explosion and micro-arc leads to a significant decrease in breakdown strength. For Al samples, surface micro-arcing reduces the breakdown strength of the polymer film by about 20%. At the same time, the effect of electrical explosion reduces it by about 30%. For Zn samples, these values are 14 and 21%, respectively. It has been experimentally shown that the breakdown strength is more sensitive to the electric power of the demetallization process, but not to its duration, at least for such fast events (lasting from ~0.1 - 10 µs). It known that an electrical explosion is accompanied by shock waves, radiation pulses, etc. These effects can complement the thermal impact on the polymer surface, which jointly leads to a more significant decrease in breakdown strength. The difference between Al and Zn can be explained by the different values of the sublimation enthalpies of these metals (including the specific heat capacity, enthalpies of fusion and vaporization). This energy is 13.1 kJ/g for Al and 2.2 kJ/g for Zn. Conversion per unit volume of metal gives 35.4 kJ/cm^3 and 15.8 kJ/cm^3, respectively. This means that the energy transferred to the polymer before the metal layer evaporates is higher for Al metallization.

Thus, it has been shown that the effect of electrodes on the breakdown strength of a polymer film might be prominent. The SH process may cause local reduction of breakdown strength, increasing the probability of new breakdowns even at lower applied voltage levels. This should be taken into account by choosing capacitor rated voltage level both.

C. Effect on volumetric capacitance

In the previous part of the article, we considered the effect of MFC electrodes on the basic electrophysical characteristic of polymer films – breakdown strength. Additionally, it is crucial to analyze other aspects of the electrode’s influence, namely the effect on the capacitor parameters – capacitance and ESR.

As mentioned earlier, MFC electrodes can be all-over, segmented and hybrid. In the case of all-over and hybrid electrodes, the capacitance is determined by the overlap area of the electrodes, excluding the margin areas that are free of the metal layer. Segmented electrodes contain areas without metallization, which form the segment structure (see Fig. 3-5), but do not contribute to the capacitance. Manufacturers offer segmented films with various geometric parameters of the segmentation pattern, depending on the capacitor's voltage rating. Segmented metallized films produced by Steinerfilm have gates of width b ranging from 200 to 800 µm and length c ranging from 100 to 500 µm (intersegment distance). The maximum reduction in the capacitance of a capacitor when using segmented electrodes can be estimated by referring to Fig. 8.

The graph shows the results of computational analysis using COMSOL Multiphysics. As seen, the maximum area reduction is 12%. For typical values of *b* and *c* (350 µm and 200 µm, respectively), the reduction in active area is 5%. This force to increase winding length of the capacitor section in order to maintain capacitance at the design level and leads to an increase in capacitor volume. Clearly, for all-over and hybrid electrodes, the active area will remain as large as possible, regardless of any electrode configuration parameters combination.

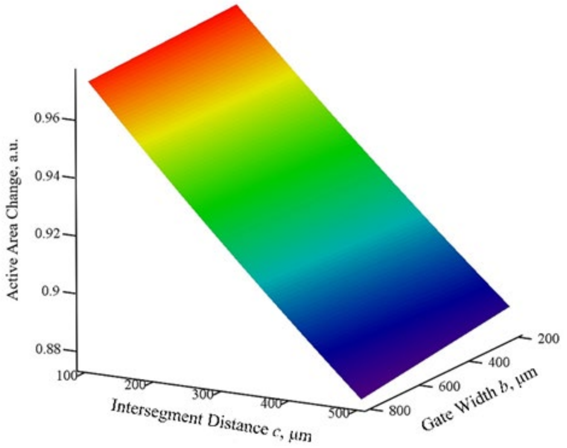


Fig. 8. Relative reducing of active area of segmented electrodes by varying geometric parameters

D. Effect on equivalent series resistance

Changing the geometrical parameters of metallization, including all-over, segmented, and hybrid types, implies the change of electrodes surface resistance R_S. The last, in turn, can significantly contribute to the ESR of the capacitor.

For of all-over metallization, the thickness (δ_{Me}) is the key geometric parameter; for segmented one – the thickness (δ_{Me}), the width (b) and the the length (c) of the gate; for hybrid one – the thickness of thin (δ_{thin}) and thick (δ_{thick}) metal layers as well as the length of the gap (c) between the segments.

The surface resistivity of the metal layer ρ_s can be determined from the dependence of the specific electrical resistance of the metal ρ on the thickness of its layer δ_{Me}:

$$\rho(\delta_{Me}) = \rho_s \cdot \delta_{Me}.$$

In case of electrodes with all-over metallization, the specific surface resistivity is identical to the surface resistance because there are no areas of electric field distortion or enhancement over the entire electrode surface:

$$\rho_s(\delta_{Me}) \equiv R_s(\delta_{Me}).$$

For example, an aluminum layer of 20 nm thickness has the resistivity about 6×10^{-8} Ω·m, which in terms of the surface resistance is approximately 3 Ohms. For zinc 20 nm layer corresponds to a surface resistance of ~6.5 Ohm.

It is of interest to evaluate analytically the electrode resistance in the case of widely used slope profile metallization, characterized by variable along the electrode width surface resistance. It is believed that profile metallization can provide low electrode losses without reducing the voltage stress due to thin metallization areas [24]. The equivalent electrode resistance for variable surface resistance is expressed by

$$R_{el} = \frac{1}{B^2 L} \cdot \int_0^B R_s(x) \cdot x^2 dx, \tag{1}$$

where B is the film width, L is the winding length, R_s is electrode surface resistance, x is the coordinate in the direction along the width of the film.

The typical electrode surface resistance dependence on coordinate along the width of the film for slope profile metallization can be expressed as follows

$$R_s(x) = R_{s0} + \beta \cdot x^n, \tag{2}$$

where R_{s0} is the surface resistance near the contact node (heavy edge), x is the coordinate in the direction along the width of the film, β = [Ω /mn], n are empirical coefficients indicating the growth of electrode resistivity with the distance.

Substituting (2) in (1), and integrating we obtain the expression for the equivalent electrode resistance

$$R_{el} = \frac{B}{3L} \cdot \left(R_{s0} + \frac{\beta B^n}{1 + n/3} \right). \tag{3}$$

It can be easily shown that for the case of non-variable surface resistivity ($\beta = 0$) the expression (3) transforms to the well-known formula

$$R_{el} = R_{s0} \cdot \frac{B}{3L}.$$

Let us demonstrate the effect of applying profile metallization on the equivalent electrode resistance. We take the experimentally measured parameters for 70 mm height PP film, shown in the Fig. 9, manufactured by Birkelbach Kondesatortechnik GmbH, with slope Zn metallization. After measurement and experimental data processing we have the parameters

$$R_{s0} = 3.15\ \Omega, \quad n = 2.13, \quad \beta = 4.1\times10^{-3}\ \Omega/\mathrm{mm}^n,$$

which correspond to the surface resistance growth from 3 at $x = 0$ to 35 Ohms at $x = 70$ mm.

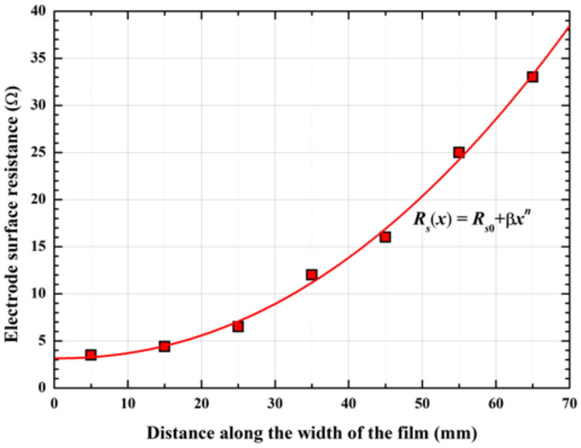


Fig. 9. Typical plot of profile metallization surface resistance.

The near quadratic growth of surface resistance with the distance along the film width is apparently caused by quadratic decrease of current square along the electrode width. In that case the loss spatial distribution would be even along the electrode width.

The relative increase of the whole electrode resistance compared with one for thick part of electrode in the case of profile metallization is

$$k_{el} = 1 + \frac{\beta B^n}{R_{s0} \cdot (1 + n/3)}. \qquad (4)$$

Substituting experimentally determined parameters in (4) we yield k_{el} = 7.48. It is quite significant increase, that should be considered by the selection of electrode system configuration. One can roughly estimate the effect of electrode resistance growth in the case of quadratic surface resistance growth as

$$k_{el} \approx 1 + 0.6 \cdot \frac{R_s(B)}{R_{s0}} \approx 8,$$

where $R_s(B)$ is electrode surface resistance near the margin.

Evaluation the surface resistance R_s for segmented and hybrid electrodes ceases to be a simple task due to the uneven current distribution and the influence of other geometric parameters on it. Fig. 10 illustrates the dependencies of surface resistances for segmented and hybrid electrodes when varying their geometric parameters, calculated by means of COMSOL Multiphysics. The graphs show that the surface resistance varies widely. This fact should be considered when selecting the proper electrode segmentation pattern.

Let's compare the surface resistances of the segmented and hybrid electrodes under fixed parameters (see Fig. 11). The metallization thickness of segmented electrode is fixed at 20 nm, and the gate width is fixed at 350 µm. For hybrid electrodes, the thickness of «thick» layer is 20 nm, and that one for «thin» is 5 nm. We vary the width of the inter-segment gap.

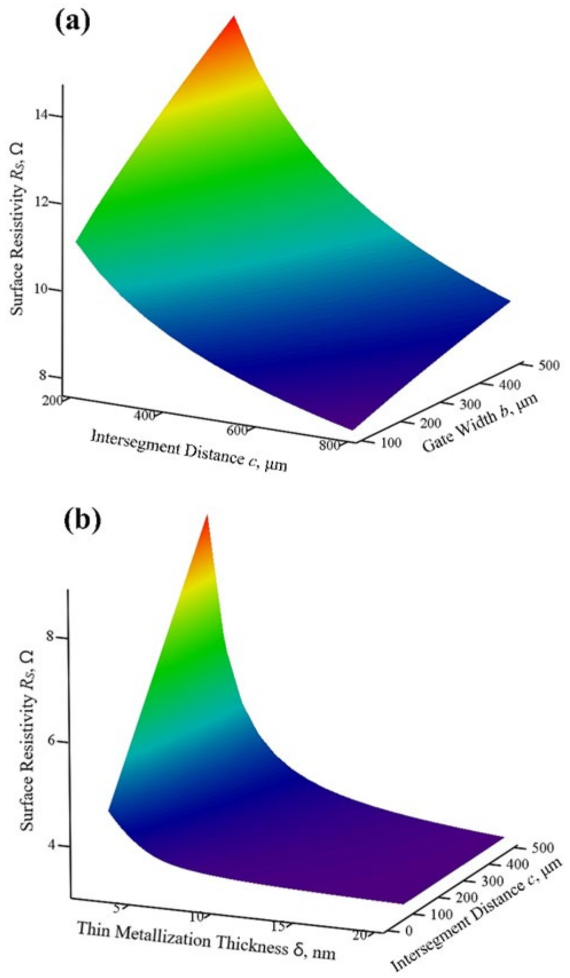


Fig. 10. Surface resistances of segmented (a) and hybrid (b) electrodes by varying geometric parameters.

The plot shown in the Fig. 11 highlights another advantage of hybrid electrodes over segmented electrodes: their surface resistance is close to that of all-over electrodes, and only slightly exceeds it. One can estimate approximately the relative increase of surface resistance for square pattern as

$$\frac{\Delta R_s}{R_s} \approx \frac{R_s^{\text{thin}}}{R_s^{\text{thick}}} \cdot \frac{c}{2 \cdot B_{segm}},$$

where R_{sthin}, R_{sthick} are surface resistances of thin and thick metal layer, respectively; c is intersegment distance, B_{segm} is the thick metallization segment side size. The relative increase of surface resistance for typical parameters $R_{sthin}/R_{sthick} \sim 10$, c = 200 µm and B_{segm} = 8 mm is about 13%.

This will not only positively affect the ESR but also the load capacity of the capacitor in terms of maximum current rating.

An important difference between segmented and all-over electrodes is the significantly lower SH energy. Energy is one of the main SH process characteristics, as it significantly affects the rate of degradation of capacitor performance and the probability of catastrophic failure. In Section 4 we will compare the energy characteristics of the SH process for electrodes based on segmented and hybrid metallization.

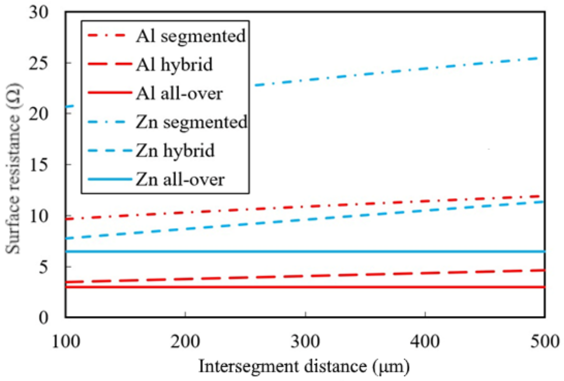


Fig. 11. Comparison of surface resistances of 20 nm thick Al and Zn electrodes: All-over, Segmented (gate width 350 microns), Hybrid (thin layer 5 nm).

III. ENERGY CHARACTERISTICS OF HYBRID ELECTRODES DESTRUCTION

The SH process in capacitor with segmented electrodes results in electrothermal destruction of intersegment gates. The energy characteristics of these processes have been studied in detail by the authors earlier [17]. Experimental dependences of specific current action integrals before destruction have been obtained, on the basis of which the developed destruction process numerical models have been verified for single gate and single segment (four gates).

Let us compare the previously obtained results with experimental data for hybrid electrodes. To obtain the energy characteristics of the hybrid electrode destruction process, an experimental setup similar to that one used earlier [17] was used, as shown in Fig. 12. Samples of hybrid electrodes of 3-5 mm width were tested, consisting of two segments with a thicker metallization δ_{thick} = 30 nm and an intersegment area with a thinner metallization δ_{thin} = 6 nm. Square voltage pulses of different amplitudes and durations ranged 10-100 μs were applied to the sample. The voltage and current across the sample during its electrothermal destruction were recorded with an oscilloscope using resistive low-inductive current probe. An example of the obtained current and voltage oscillograms is shown in Fig. 13. Several series of experimental samples of hybrid electrodes with different combinations of «thick» and «thin» layer thicknesses were produced.

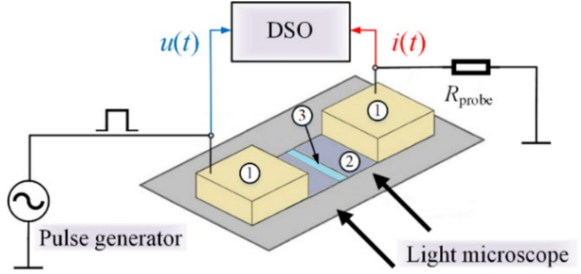


Fig. 12. Experimental setup for hybrid electrodes destruction investigation: 1 – brass electrodes, 2 – segments with thick metal layer, 3 – intersegment area with thin metal layer.

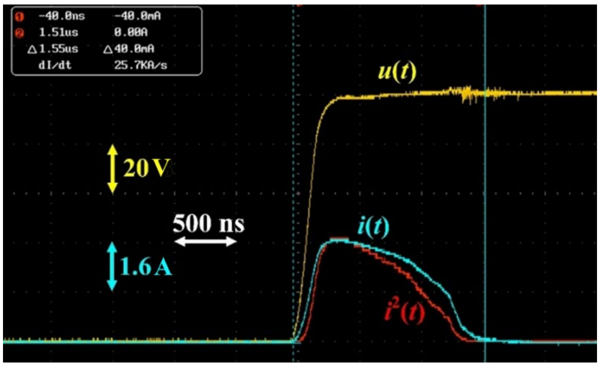


Fig. 13. Voltage and current waveforms of hybrid metallization destruction process.

More than 10 different combinations of thicknesses (and surface resistances R_s) of Al layers were studied. At least 30-40 samples of each thickness ratio were used to study the destruction of hybrid metallization of different combinations of segment-intersegment thickness. It was found that most of the combinations resulted in the expected failure of the intersegmental region.

Destruction of the samples consisted of the growth of a demetallization "crack" in the intersegment region with reduced metal thickness in direction transverse to the current flow over the entire width of the sample. Example of microphotograph of destruction zone in transmitted light is shown in Fig. 14.

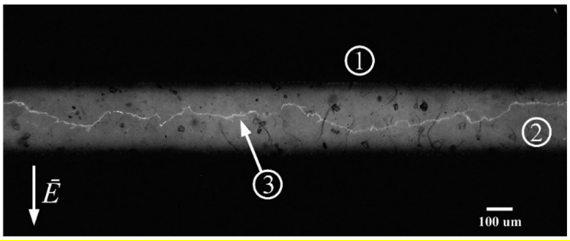


Fig. 14. Photograph of destructed sample of hybrid electrodes with 6/30 nm thickness ratio: 1 – thick

metal layer, 2 – thin metal layer, 3 – demetallized zone. Arrow is for electric field direction.

The photograph shows that the width of the demetallization crack is quite small. For a more detailed analysis of the destruction zone, images were taken with a Phenom ProX scanning electron microscope (see Fig. 15).

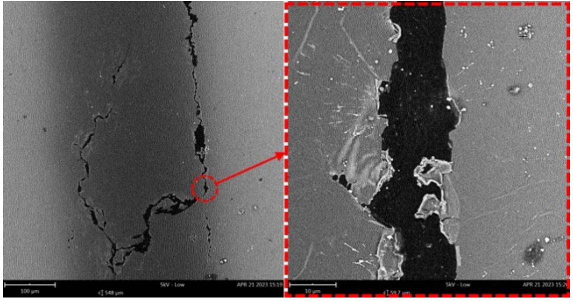


Fig. 15. SEM photographs of demetallized zones.

Using the obtained SEM images, it was possible to determine characteristic sizes of demetallization cracks in the cross section. They are about 10 microns. At the same time, the explosive character of metallization destruction, characteristic for thicker metallization layers, is persisted.

The specific action integral is a characteristic of fuses electric explosion process very useful to evaluate its cut-off ability. Fig. 16 shows the experimental values of the specific current action integral before destruction of the segmented electrodes samples with a thickness of 10 nm and hybrid electrodes with a thickness ratio of metal layers of 6/30 nm.

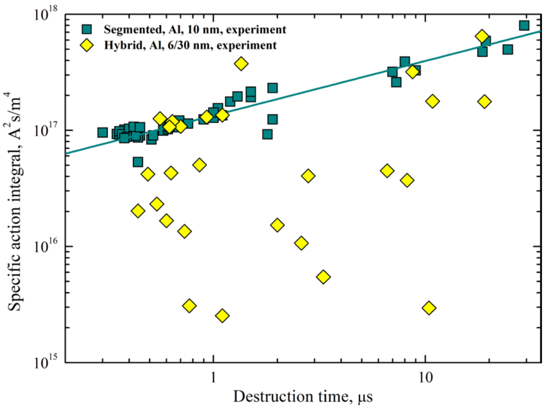


Fig. 16. Experimental current specific action integral vs. destruction times for segmented and hybrid electrodes.

As can be seen from the results of the comparison of the destruction process energy characteristics, the energy required for electrothermal destruction of the hybrid electrode is, on average, several times lower than that required for segmented ones. The scatter of the data can be explained by the difficulty of producing laboratory samples of hybrid electrodes with identical geometric parameters. Nevertheless, it can be concluded that the energy dissipated during the SH will also be significantly lower due to short duration of process, which will have a positive effect on reducing the probability of catastrophic capacitor failure. It's worth noting, that hybrid electrodes as well as segmented ones allow tailoring of their configuration parameters obtaining required SH duration.

In addition, pilot experiments on dielectric breakdown and consequent SH were performed on several laboratory samples of PP films with hybrid metallization. Fig. 17 shows examples of hybrid electrode operation by single and multiple breakdowns of the polymer film.

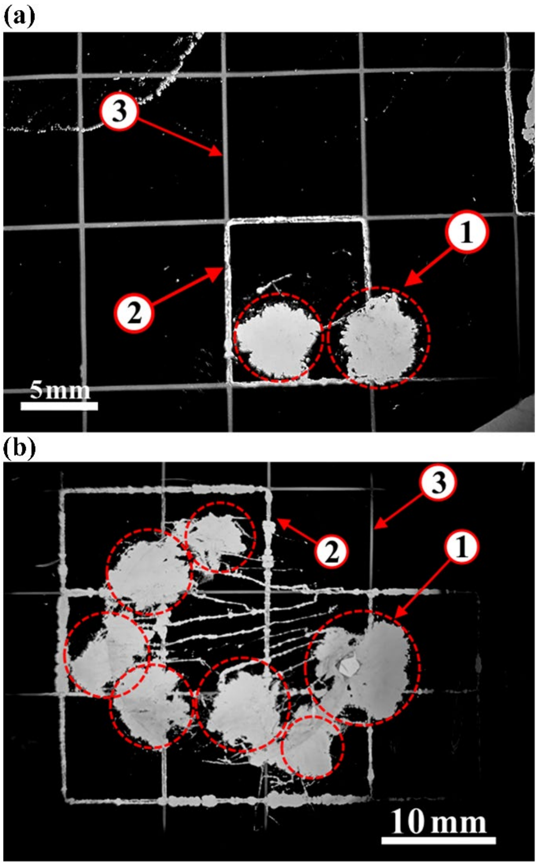


Fig. 17. Photographs of breakdown site in hybrid electrodes: (a) – one segment isolation, (b) – group of segments isolation. 1 – demetallized zone around breakdown channel, 2 – demetallized intersegment area, 3 – undestructed intersegment area.

As can be seen from the photos, the isolation of a damaged segment and a group of segments occurs according to the correct scenario. Intersegment area surrounding damaged segments is subjected to burnout, which makes it possible to cut off these damaged segments from the intact part of the electrode.

At the moment, studies are in progress to refine the technology and obtain samples with high reproducibility of the metallization geometric characteristics, in order to extend this experience to the production of metallized films in roll-to-roll mode.

IV. CONCLUSION

As a result of conducted research, the influence of electrodes configurations (all-over, segmented and hybrid) on the MFC performance metrics was investigated and some approaches to proper electrodes' configuration selection are described.

The influence of metallization thickness on breakdown strength of MFC is caused by a thermal impact of deposited metallic atoms on polymer film. We showed that the reduction of breakdown strength can reach tens of percent depending on the metal layer resistivity. Along with that the subprocesses of SH such as electric explosion of metallization and micro arcing lead to local polymer breakdown strength decrease. The decrease amounts up to 25 % in the case of aluminum metallization electric explosion.

Also, the influence of geometric parameters of segmented metallization pattern was demonstrated using computational analysis. It was found that the maximum possible decrease in capacitance reaches 12%, the typical decrease is at the level of 5%.

We analyzed the effect of electrodes parameters such as thickness, geometry of pattern on equivalent electrode resistivity for various metals and geometries used in MFCs. Our findings show that the application of widely used slope profile metallization results in typical increase of electrode resistivity of 5-10 times compared to that one of zones with thick metal layer. The effect of segmentation on electrode resistivity was estimated by numerical simulation. It was demonstrated that the increase in equivalent resistivity reaches up to 5 times in comparison with all-over metallization of the same thickness.

We proposed a hybrid type of electrodes' configuration, which combines the benefits of segmented and all-over electrodes. A typical raising of proposed hybrid electrode resistivity is about 30%, as compared to all-over electrode. The resistivity of hybrid electrode was characterized by numerical analysis for various parameters, as result the increase of resistivity was found to be 5-10 times less by average than that one for segmented electrode with the same intersegment distance. We established the sufficient cut-off ability of hybrid electrode during self-healing test. In addition, the destruction of hybrid electrodes requires an order or two less energy than for segmented ones that provides a fast damaged segment cut-off and lower level of self-healing energy than for all-over electrodes.

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