SELF-HEALING METAL FILM CAPACITORS: QUO VADIS?

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Abstract. Metal film capacitors are ubiquitous components in modern electronics, playing an important role in energy storage, filtering, and voltage regulation. However, their performance and reliability can be reduced by partial electrical breakdowns caused by defects in the dielectric material. An attempt to partially mitigate this problem are self-healing capacitors, which have the ability to recover after an electrical breakdown. The self-healing phenomenon significantly increases the service life of the device. This review presents a comprehensive analysis of the currently known self-healing mechanisms in metal film capacitors. The role of the self-healing phenomenon in increasing the number of capacitor working cycles is discussed. The molecular processes underlying the significantly different self-healing potential of dielectric polymers are verified. The review is addressed to specialists in electrical engineering.

Keywords: dielectric capacitor; metal film capacitor; electrical breakdown; self-healing; polymer; molecular modeling.

1. Introduction

Capacitors are passive electronic components that store electrical energy in an electric field. Dielectric capacitors consist of two conducting plates (electrodes) separated by an insulating material called a dielectric (Fig. 1). The capacitance of a capacitor, which numerically determines its ability to store energy, is directly proportional to the permittivity of the material and the area of the plates and inversely proportional to the distance between them (Tahalyani et al., 2020).

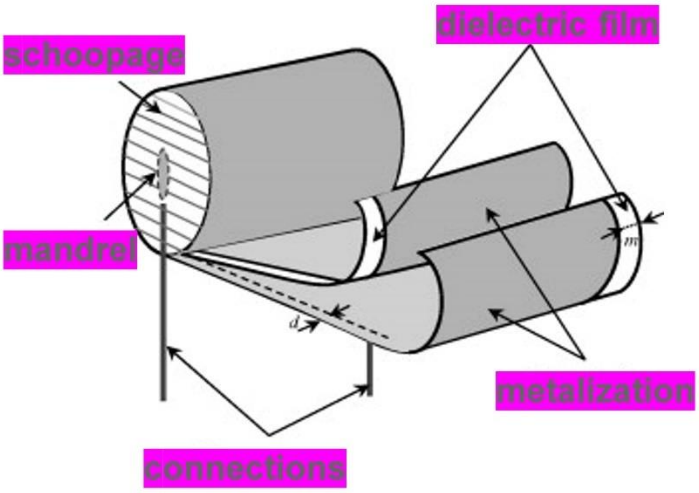

Fig. 1. Simplified design diagram of a metallized film capacitor. The figure is modified based on (Makdessi et al., 2014).

Today, there are two types of film capacitors: with foil and metallized electrodes. They differ in design and some characteristics. Below, we will briefly point out the difference in the design of these devices and the operating features caused by this difference.

In foil capacitors, the plates are thin metal foils (usually aluminum or zinc-aluminum), separated by a dielectric. Such capacitors have a stable high capacity, but when the dielectric breaks down in a foil capacitor, a short circuit occurs, as a result of which the capacitor fails. Such capacitors do not have self-healing properties. Another disadvantage of such capacitors is their relatively large weight and dimensions.

Aluminum, zinc, and more often a combination of both are used as electrodes, the thickness of which varies from 5 nm to 30 nm. When the dielectric in a metallized capacitor breaks down, local evaporation of the metal and film occurs at the breakdown site. Due to evaporation, a demetallization region is formed, which isolates the breakdown channel. This allows the capacitor to almost completely restore its operational properties after minor overloads. This phenomenon is called self-healing (SH) of the capacitor.

Due to the thin metal layer, metal film capacitors can be smaller than foil capacitors for the same device capacitance. However, thin metal layers are more susceptible to corrosion than foil, which can lead to some changes in capacitance over time or with temperature changes.

Dielectric materials play a crucial role in the performance of a capacitor, determining its capacitance, operating voltage, and stability. However, dielectric materials are subject to electrical breakdown, a phenomenon in which the insulating properties of a material deteriorate. Eventually, the accumulation of electrical breakdowns leads to a short circuit of the electrodes. This can occur due to various factors, including structural imperfections in the dielectric material, unexpectedly strong electric fields, and local overheating (Lin et al., 2024).

Self-healing capacitors offer a solution to this problem. The mechanisms that allow them to recover from electrical breakdown are currently the subject of active study. The ability to self-heal significantly increases the reliability and service life of capacitors, making them attractive for previously unconsidered applications. Metallized film capacitors are well suited for high-frequency and high-voltage electrical fields, such as electric vehicles, aerospace, and pulsed power systems, precisely because of their self-healing properties (Li et al., 2015; He et al., 2023b; Yang et al., 2010; Ennis et al., 2002; Venkat et al., 2010).

In this paper, we provide a detailed review of the latest scientific literature on MFCs and SH processes in them. For the first time in review publications on this topic, we consider SH from both macroscopic and microscopic points of view. The phenomenon of soot formation from evaporated electrodes and polymer insulation material, its chemical composition, volatile by-products, and electrical conductivity are discussed.

2. Results and discussion

Mechanisms of self-healing of the MFC. Phenomenon SH in dielectric capacitors typically involves evaporation of the electrode material near the breakdown site. This process effectively isolates the breakdown site, preventing further structural damage and restoring the functionality of the capacitor. Several mechanisms contribute to SH (Fig. 2) depending on the materials and design of the capacitor (Wu et al., 2024a; Zhang et al., 2023).

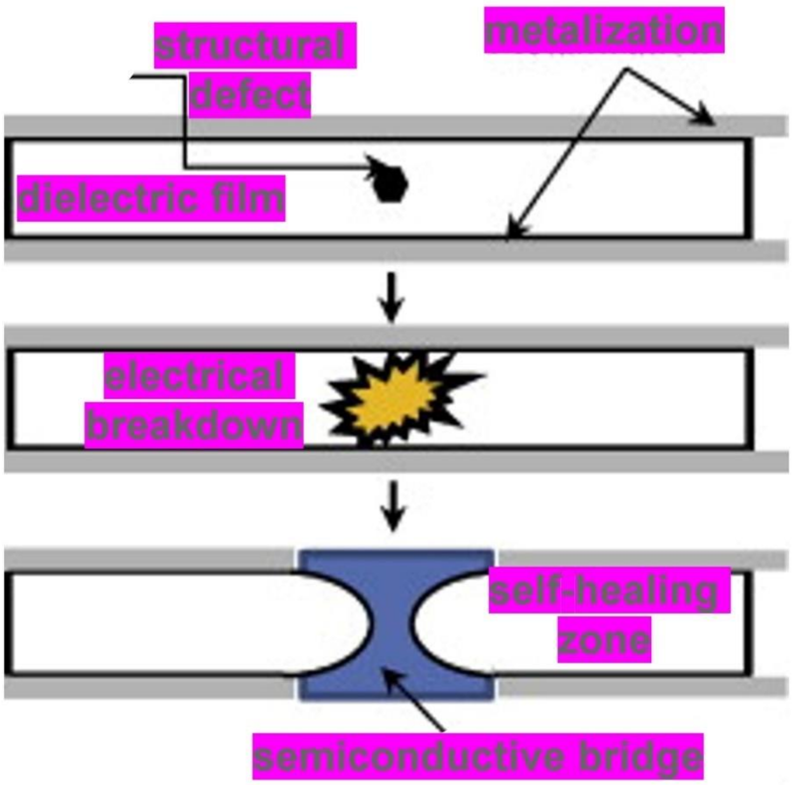

Fig. 2. Schematic explanation of the self-healing phenomenon in metallized film capacitors. The figure is modified based on (Makdessi et al., 2014).

Evaporation of metallized electrodes: In capacitors with thin metallized electrodes, electrical breakdown generates intense heat, causing the metallization near the defect to evaporate. This evaporation creates a gap in the electrode, isolating the defect and preventing further current flow (Du and Zhang, 2024). During the SH process, part of the released thermal energy is spent on heating the dielectric layer. When exposed to very high temperatures, the dielectric is carbonized and evaporated. In this case, the area of destruction of the metal layer, as a rule, exceeds the area of evaporated dielectric. This observation allows us to conclude that the heat of electrical breakdown spreads much more easily through the metal than through the dielectric.

After the dielectric breakdown and the electric arc extinguishing, the evaporated material cools and settles in the SH region in the form of a soot (carbonized) layer. The resulting soot can form a semiconductor channel and disable the capacitor. The efficiency of the SH depends on (1) the dielectric properties of the soot, (2) its quantity, and (3) the proportion of gas products formed during the SH process (Chaban and Andreeva, 2024a).

Experiments show that the thickness of the dielectric layer has a negative effect on the quality of the capacitor. Increasing the tension force to 20-30 N during winding of capacitors in production, on the contrary, has a positive effect. The result of theoretical modeling based on plasma theory shows a depth of 0.28 μm in the carbonized region, which is 5% of the dielectric layer thickness of 5.8 μm. In addition, the radius of the carbonized region in the dielectric exceeds the evaporated region in the metallized layer by one and a half times (Wu et al., 2024b).

Criteria and reasons for refusal of the MFC. There are two types of failure of the MFC: parametric and catastrophic. In case of parametric failure, as a result of operation, there is a decrease in the key parameters of the capacitor. Usually, this is a decrease in the capacitor capacity by 5% (less often 10%) or an increase in the dielectric loss factor by 2 times . In the event of a catastrophic failure, a short circuit of the MFC or an open circuit occurs. (Gupta et al., 2018; Lv et al., 2023).

Capacitors based on polypropylene (PP) film do not fail during a short circuit, but tend to lose capacity. As a result of each act of short circuit, part of the metallized film burns out, which means that the area of the metallization zone decreases. This effect is cumulative. As a result of operation, the capacity of the MFC is systematically reduced (Xiao et al., 2024b; Xiao et al., 2024a).

Some dielectric materials exhibit low potential to SH in the MFC. In this case, the capacitor may fail even in the case of a single act of dielectric breakdown. The capacitor plates short-circuit, and a catastrophic failure occurs. The worst properties to SH are polyphenylene sulfide (PPS) and polyimide (PI) (Cao et al., 2023)These insulating materials shorten the service life of the MFC, although they give the capacitor excellent resistance values.

When a breakdown occurs, an electric arc with a temperature of over 3000 K is formed at the defect site, causing part of the polymer and metal to burn out. The high density of the resulting gas phase leads to an increase in pressure in the breakdown area. As a result of increased pressure, the mechanical strength of the MFC elements may be lost – delamination or rupture of the metallized film. Pressure above critical may lead to destruction of the capacitor housing and its irreversible failure.

After the SH phenomenon, a soot layer forms at the breakdown site. If the soot channel accidentally short-circuits the capacitor plates, a charge leak occurs, the capacitor loses capacity and fails. It is believed that the quality of the SH depends on the conductivity of the soot channel and its thickness. A simple formula showing the ratio of the number of elements included in the composition of non-volatile compounds to the number of elements included in the composition of volatile compounds allows an approximate estimate of the volume of soot formed as a result of the breakdown. (Ho and Greenbaum, 2018):

$$f = \frac{C + N + S}{O + H} \text{ или } f = \frac{C}{O + H} \ .$$

According to the given formula, conjugated high-temperature polymers with a high degree of carbon unsaturation exhibit a high index, for example f = 1.47 for Kapton polyimide compared to f = 0.5 for PP. The higher the f index, the lower the ability to SH (Walgenwitz et al., 2004; Ren et al., 2024). The reader's attention should be drawn separately to the conventionality of the definition of "volatile" and "non-volatile" elements. For example, the so-called "non-volatile" elements - carbon, nitrogen and sulfur - can also generally form volatiles, but in the condenser context, due to thermodynamic and stoichiometric factors, they prefer to remain in the composition of non-volatile soot.

The reasons leading to the failure of the MFC can be: (1) chemical corrosion due to humidity, (2) electrochemical corrosion, (3) overheating and melting of the dielectric film (Yao et al., 2024a). Atmospheric corrosion significantly reduces the service life of the MFC. Moisture and oxygen, penetrating into the device, cause oxidation of the electrodes, increasing their resistance and leading to a loss of capacity. Studies have shown that the structure of the oxide film on the electrodes, depending on the aluminum content, determines the anticorrosive properties of the MFC. Increasing the aluminum content to 50% or more allows for effective protection of the end contacts from corrosion. Accelerated tests under high temperature and humidity conditions confirmed that the polymer film of the capacitor degrades, and the electrodes oxidize. Modeling the aging process made it possible to determine that temperature has a stronger effect on corrosion than humidity (Li et al., 2023; Tai et al., 2022; Qiu et al., 2022).

Self-healing characteristic. The following methods are used to characterize the properties of SH capacitors. To evaluate the SH of a capacitor, its breakdown voltage is often examined, evaluating the result obtained using the Weibull distribution. The Weibull distribution is a statistical method widely used in various fields, including physics, engineering and materials science, to describe the distribution of extreme values, such as breakdown voltages. Based on the obtained distribution parameters, conclusions can be made about the average value of the breakdown voltage, the spread of breakdown voltage values, the probability of breakdown at a given voltage (Yan et al., 2024).

The SH energy in the MFC is the amount of energy required to restore the insulating properties of the capacitor after a local dielectric breakdown. In other words, this is the energy that is released during a short circuit at the defect site and is spent on evaporating the electrode metal, which leads to the insulation of the damaged area and the restoration of the capacitor's performance. The SH energy determines the size of the evaporated area in the metallized electrodes of the MFC. Lower SH energy guarantees a smaller evaporated area, lower capacity losses and a longer service life (Li et al., 2013; Chen et al., 2011).

Peng et al. investigated the correlation between the SH energy and critical factors such as peel stress (adhesion between films), damage to internal components, and the number of damaged layers for a metal film capacitor with a polypropylene dielectric. At safe SH levels (< 100 mJ), the peel stress on metallized films remains below 8 N/m, while hazardous SH events (> 250 mJ) lead to an increase in peel stress to 14 N/m. (Pan et al., 2024).

Electrical measurements – SH duration, breakdown field strength, SH current and SH energy – can be used to monitor capacitor performance after electrical breakdown. Thermal imaging technology can help understand the relationship between short-circuit points and temperature gradient. Changes in these parameters can indicate the occurrence and quality of SH (Zhou et al., 2024).

Microscopy techniques such as scanning electron microscopy and transmission electron microscopy can be used to visualize the breakdown location and characterize the SH (Wu et al., 2024b). These techniques reveal the morphology of the electrode and dielectric materials, which provides insight into the SH mechanisms (Wu et al., 2024c). Accelerated aging methods are often used to evaluate the SH efficiency. When the capacitor capacitance decreases by 5%, it is unwound and the area of the SH points is estimated along with their spatial distribution. In this case, pattern recognition technology is used (Yao et al., 2024b).

The SH in metallized films consists of incomplete but intense combustion producing gaseous products such as C_2H_2, C_2H_6, CO, H_2 and some others in smaller quantities. Due to its considerable thermodynamic stability, the mole fraction of H_2 is most often the most significant. On the other hand, the SH process does not lead to the formation of polar fragments in the dielectric layer, as shown by Fourier transform infrared spectroscopy (FTIR). Scanning electron microscopy shows a strong correlation between the SH phenomenon and charring on the surface of the dielectric layer. It was found that a small number of metallic elements remained in the SH region without metal oxide particles. However, a large amount of graphite was found in the cleaning region together with a certain amount of chemically bound oxygen (Wu et al., 2024b).

Energy dispersive X-ray spectroscopy and X-ray photoelectron spectroscopy can be used to analyze the elemental composition and chemical state of materials at the breakdown site. This can provide information on the evaporation or migration of electrode materials during SH (Pourpasha et al., 2024). Thermal analysis techniques – differential scanning calorimetry and thermogravimetric analysis – can be used to study the thermal properties of materials and their behavior during electrical breakdown. This can provide insight into the thermal stability of the MFC and the heat released during SH (Ritamäki et al., 2017).

Finite element calculations help to obtain the characteristics of the field distribution in a metal electrode (Yi et al., 2024). Simulations demonstrate that a hole in the electrode causes a change in the direction of the current. The current concentration occurs at the upper or lower edge of the hole notch, which leads to a higher current density and power density in this region than in other regions (Wang et al., 2024). Also, the finite element method was used to simulate the interruption of the filamentary breakdown current, when a thermally induced increase in the series resistance in the electrode metallization destabilizes the breakdown plasma arc (Christen et al., 2024).

One of the parameters characterizing the SH is the value of cumulative energy. The SH energy in a capacitor can be expressed as follows (Tortai et al., 2005):

$$W = \frac{k \cdot V^{4.7} \cdot C}{R_S^{1.8} \cdot \alpha(P)}.$$

Here k – coefficient, V – working voltage, C – capacitance of the tested capacitor, R_s – surface resistance (Ohm/square, Ω /□) of the metallized film, α(P) – a function that relates the interlayer pressure to the energy of enlightenment.

Methods of molecular modeling help to systematically study the macroscopic properties of a material based on their molecular structure. Using the method of classical molecular dynamics, the interaction of new dielectric liquids based on dialkyl carbonates with the most commonly used polymer films in MFCs – PP, PET and cellulose – was studied. As a result, it was found that diethyl carbonate is better suited for filling pores (“impregnation”) in cellulose, while didodecyl carbonate is better suited for PP and PET (Chaban and Andreeva, 2022a). The compatibility of various impregnating liquids with various polymers is based on the intermolecular forces of interaction between the dielectric and the liquid, the size of the micropores in the dielectric, and the flexibility of the molecules of the impregnating liquid (Fig. 3). The studied organic carbonates were recommended for use in capacitor technologies instead of mineral oils.

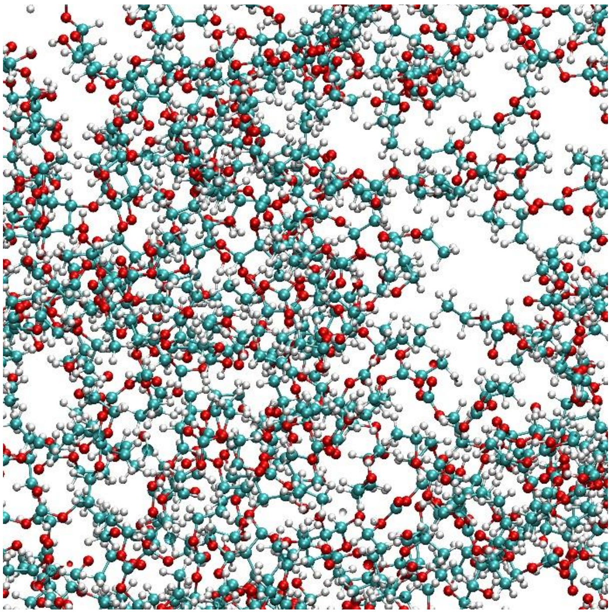

Fig. 3. Spatial distribution of liquid diethyl carbonate molecules over the volume of solid cellulose during equilibrium modeling using classical molecular dynamics. Instantaneous molecular configuration at 298 K. Carbon atoms are blue, oxygen atoms are red, hydrogen atoms are white.

Using the kinetic energy injection method (Chaban and Andreeva, 2024b; Chaban and Andreeva, 2022b; Chaban and Andreeva, 2022c) adapted to the study of high-temperature chemical reactions, it is possible to study the potential energy surface to detect samples of soot formed in the SH process. For the obtained chemical compositions at low-energy stationary points, it is possible to calculate the values of electrical conductivity, the width of the forbidden band, and infrared vibrational spectra (Fig. 4) using the methods of the density functional theory. We draw attention to the fact that in the above calculations, the configurations of the global minimum of energy and other lowest-energy configurations within a few kT units from the global minimum should be used. These theoretical calculations are indispensable in the design of new, more reliable MFCs.

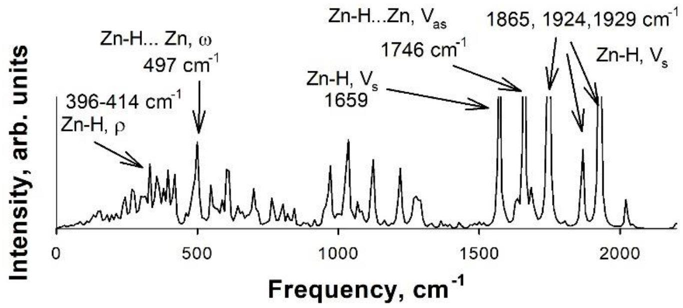

Fig. 4. Vibrational spectra of a soot sample in the mid- and far-infrared region, in the system of chemical composition Zn (electrode) + PP (dielectric). Calculations were performed using the density functional theory method, unrestricted M11/6-31G* for carbon and hydrogen and the LANL2DZ basis set for zinc atoms, for the global minimum energy sample.

The chemical composition and amount of gas products formed after electrical breakdown fundamentally affect the SH. Gas products have zero electrical conductivity, so their molar fraction is directly proportional to the SH quality. Moreover, gas formation obviously reduces the volume of ungasified soot. Small volumes of soot have proportionally small probabilities of becoming semiconducting bridges between the electrodes of the self-healing MFC. Thus, the possibility of a short circuit is virtually eliminated. Varying the elemental composition of the MFC allows one to obtain devices that are more or less prone to SH. Using the reactive molecular dynamics method, we studied samples of soot formed as a result of electrical breakdown of PP, PET, PPS and PI dielectrics. The studies have shown that by the mass fraction of gas fractions, the most widely used polymers today are ranked in the following order: PP > PET > PPS > PI. The greatest influence on the formation of gaseous products is exerted by the proportion of hydrogen in the original polymer. In addition, in the soot samples obtained as a result of the modeling, small-sized graphene-like structures with conjugated π-π bonds were identified, increasing the electrical conductivity of the studied structures (Chaban and Andreeva, 2024a).

In the case of polymer insulators, where the amount of soot formed is significant, it is necessary to analyze the electrical conductivity of the obtained samples. In the context of computer modeling, this can be realized using plane waves as a basis set to adequately represent the electronic structure of a macroscopic-sized soot sample, and a second-generation density functional, for example, PBEPBE (Perdew et al., 1996). In this case, it is fundamentally important that the periodic chemical structure for calculating the electrical conductivity (Fig. 5) be based on the microscopic configuration of the calculated global minimum or another accessible, sufficiently low-energy structure that convincingly represents the soot of the destroyed dielectric.

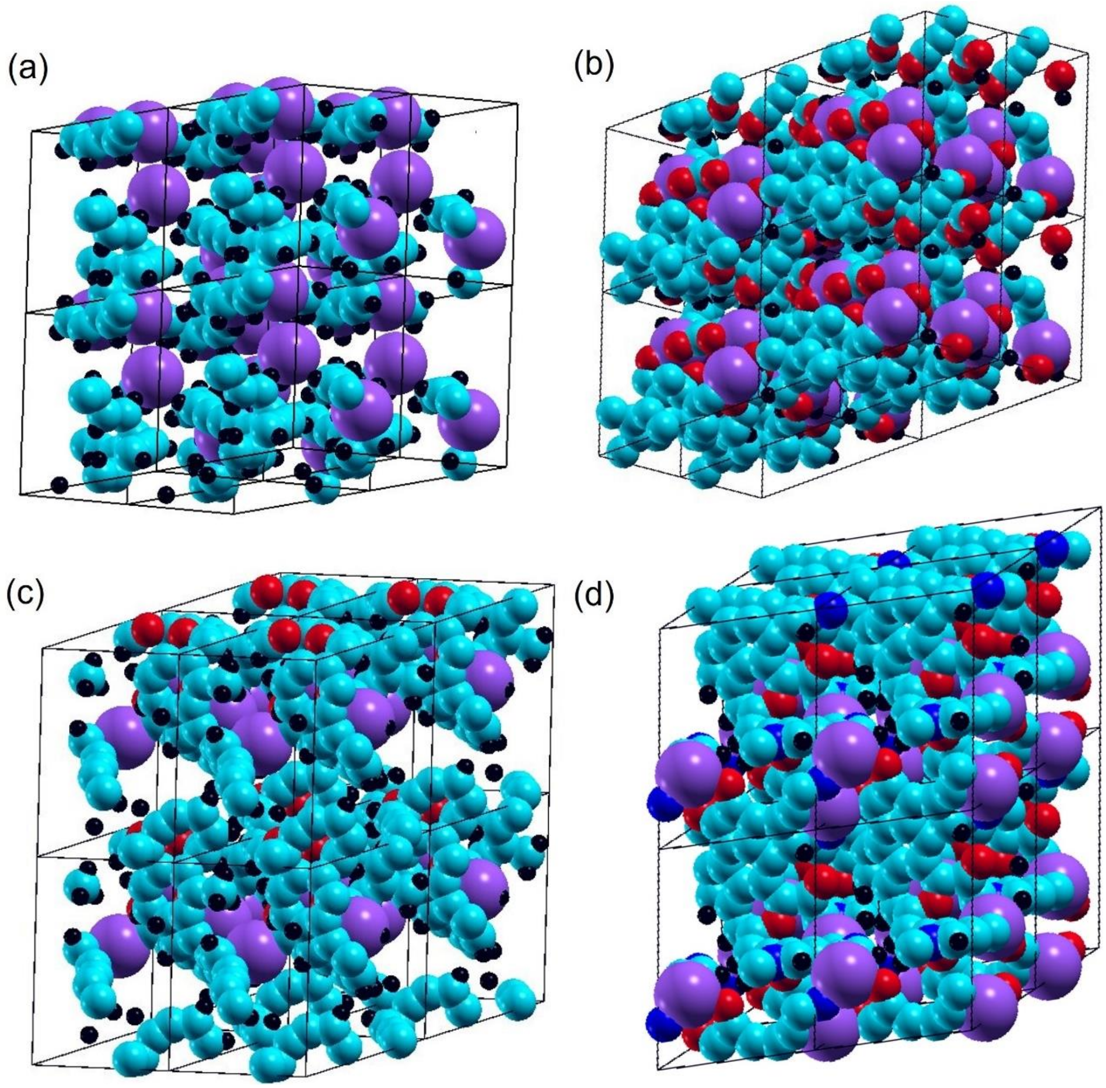

Fig. 5. Periodic structures in soot samples obtained for the following systems: (a) 4Zn + PP, (b) 4Zn + PET, (c) 4Zn + PC, and (d) 4Zn + Kapton . The

structures shown correspond to the geometries of the systems at their global minima. Volatile products have been removed from the molecular representation. Carbon atoms are blue, oxygen atoms are red, nitrogen atoms are blue, zinc atoms are violet, and hydrogen atoms are black.

Machine learning models are becoming a tool in design, including capacitors. Some scientific fields require enormous computational resources to sample the space of options. For example, to study only the most commonly used elements of the periodic table, it is necessary to study 10^{80} potential landscapes of different chemical compositions, while only about 10^{4} different types of synthetic materials have been developed. Ultimately, it is this versatility that leads to the diversity of observed natural phenomena and life forms. “Artificial intelligence” algorithms can be used for advanced property prediction, microstructure recognition, experiment optimization, and performance monitoring (Liu et al., 2024; Yue et al., 2022; Zhang et al., 2024a).

Materials for metal film capacitors. The efficiency, reliability and service life of capacitors directly depend on the correct choice of materials. Dielectric capacitors, due to their materials, have the following advantages: high energy density, fast response to voltage changes and a long service life. These properties make them indispensable in power engineering and electronics, where high performance and reliability of components are required (Su et al., 2023). Some dielectric and electrode materials have already been studied for their SH properties, but most of them are still too limitedly studied. Researchers and engineers need to understand the limits of SH capabilities and ways to modify known dielectric materials in order to minimize the likelihood of the formation of semiconducting bridges connecting the electrodes of the MFC after electrical breakdown.

Traditionally, aluminum and zinc are used as universal materials for electrodes in MFCs. Modern technologies have made it possible to replace them with zinc-aluminum alloy, thereby improving the average characteristics of capacitors. The process of manufacturing the electrode involves vacuum deposition of a metal material on a dielectric film, forming a very thin conductive layer (from 10 to 50 nm). The phenomenal thinness required for the electrode output leads to increased surface resistance (Li et al., 2022).

Atmospheric corrosion reduces the service life of MFCs due to electrode oxidation and capacity loss. Li et al. developed a model to predict this process and conducted accelerated aging tests. The results showed that corrosion significantly depends on the roughness of the dielectric film and the composition of the electrode. The optimal mass content of aluminum in the electrode is about 10% (Li et al., 2022)Thus, it is more appropriate to talk about a small addition of aluminum to the zinc electrode to improve the performance characteristics of the MFC.

The electrode structure and interlayer air affect the service life of polypropylene film-based MFCs (PPMFCs). When a strong electric field is applied, the air is ionized and increases the area and duration of the SH process in the PPMFC. Also, in a segmented PPMFC, the SH areas are concentrated mainly at the segment boundaries. Thus, choosing an electrode circuit with the smallest number of segments is a way to increase the service life. In addition, the service life of capacitors in pulsed applications can be increased by a maximum of 5 times by strengthening the winding, sealing the ends after vacuum, optimizing heat treatment in vacuum, and impregnating in vacuum (Chen et al., 2011). The capacity of the PPMFC is lost faster with alternating applied voltage than with direct voltage (Yi et al., 2019; Li et al., 2024).

Polymers such as polypropylene, polyethylene terephthalate, polyethylene naphthalate, polycarbonate and polyphenylene sulfide are widely used in self-healing capacitors (Pechnikov et al., 2024; He et al., 2023a; Wehe and

McMahon, 2016; Venkat et al., 2010), but expanding this list seems appropriate and beneficial. For example, Jiafeng Zhu et al(Zhu et al., 2023)evaluated the SH ability of metallized high-temperature dielectric films made of polyethylene-2,6-naphthalate, polyether ketone and polyimide. It was found that the high carbon content of PI leads to SH failure at low layer resistance, although it exhibits small SH energy at high layer resistance. The probability of good SH of metallized polyether ketone film is significantly reduced at high interlayer pressure. Moreover, high SH energy is achieved in polyether ketone, which would lead to rapid aging of MFC (Zhu et al., 2023). In contrast, polyethylene-2,6-naphthalate with relatively low carbon content and aliphatic -aromatic alternating structure exhibits excellent SH ability at different layer resistances and interlayer pressures with reasonable SH energy. Therefore, polyethylene-2,6-naphthalate is a promising candidate for high-temperature MFC in the context of SH (Zhu et al., 2023).

In the work of Kao et al(Cao et al., 2023)a series of dielectric films made of polyetherimide (PEI) were developed and manufactured. The introduction of polar groups helps to increase the permittivity, and the mobile ether groups help to reduce the dielectric loss. Moreover, oxygen atoms contribute to the SH of metallized film capacitors. For PEI, the permittivity of 3.53-4.00, the dissipation factor of 0.281-0.517% and the Weibull breakdown strength of 347-674 MV m^{-1} were obtained (Cao et al., 2023).

Existing high-temperature polymers for MFCs are usually based on robust aromatic molecular structures to ensure stability at elevated temperatures. However, the introduction of aromatic units compromises the dielectric properties of the polymer due to conjugated π–π bonds that facilitate electron transfer and reduce the efficiency of the SH after breakdown due to their high carbon content. Chen et al. (Chen et al., 2023)investigated an aromatic- free polynorborne copolymer that exhibits electrical conductivity two orders of magnitude lower than that of the state-of-the-art polyetherimide at elevated temperatures and high electric fields due to its large band gap (≈4.64 eV) and small hopping conduction distance (≈0.63 nm). Density functional theory calculations show that the copolymer suppresses the excitation of valence electrons in high fields. The inclusion of trace amounts of semiconductors results in high discharge density (3.73 J cm $^{-3}$) and charge-discharge efficiency (95% at 150 ° C), outperforming currently available high-temperature dielectric polymers. The excellent ability of this copolymer film to SH at elevated temperatures highlights its potential for use in MFCs. Such devices are capable of continuous operation under extreme conditions (Chen et al., 2023).

It has been established that capacitors with a PPS dielectric have an extremely low ability to SH. For each tested capacitor, no more than 5 SH events were observed, after which a catastrophic failure occurred. A small number of SH events corresponds to a low value of cumulative energy, which does not exceed 100 mJ. The low ability to SH can be explained by the chemical specificity of soot, which is formed as a result of electrical breakdown of this polymer film at the molecular level. (Pechnikov et al., 2024).

At present, it has become obvious that there is a need for research into the creation of polymer composites with improved dielectric properties, including the ability to achieve high-quality SH. However, the number of reports on such projects in the open international literature remains very limited. For example, perovskite quantum dots were created using thermal injection (Ye et al., 2024)and added to polyetherimide (PEI). The synthesized composite material showed a decrease in conductivity losses at high temperatures. The resulting PEI composite demonstrates improved energy capacity and dielectric reliability, for example, an energy density of 7.2 J/cm^3 with an efficiency of 90% at 350 MV/m, achieved in a composite containing 0.3% PEI at 100 °C (Ye et al., 2024)Reducing the cost of production of this and similar materials could allow them to be introduced into mass production.

Influence of external factors. The efficiency of the SH process can significantly depend on the thermodynamic conditions of the process. This section examines the influence of such factors as temperature, voltage, pressure, frequency and dielectric characteristics on the speed and quality of SH. Understanding these mechanisms will allow optimizing the operating conditions of capacitors and developing new materials with improved electrical characteristics. In the work of Pechnikov and Hojamov (Pechnikov and Hojamov, 2023)presents experimental studies of SH in MFC: the duration of the process and the time-dependent resistance of the microarc discharge at real interlayer pressures typical for MFC. It was found that the insulation resistance of stacked metallized polypropylene films after SH under high pressure decreases, which leads to current leakages. The occurrence of current leakages is associated with possible carbon deposition near the breakdown channel due to polymer decomposition in the high-temperature arc discharge (Pechnikov and Hojamov, 2023).

As the interlayer pressure increases, more breakdowns occur at low electric field strengths. For example, at 2.5 kPa, most breakdowns occur in the electric field strength range of 300-350 -V/μm; while at 900 kPa, most breakdowns occur at electric field strengths below 200 V/μm (Zhu et al., 2023). In addition, high interlayer pressure in the MFC helps to reduce the capacitance loss during the SH process. Studies have shown that with increasing pressure, the strength of the insulating layer can decrease and the area capable of SH can decrease. These two effects are antagonistic within the MFC. The breakdown characteristics of metallized polypropylene film at pressures of 20 kPa-1000 kPa were studied. The breakdown field of the metallized film significantly decreases with increasing pressure in the system. Large electrode losses under a strong electric field can be prevented by increasing the pressure. Therefore, increasing the interlayer pressure to a certain extent contributes to the reliability of the capacitor (Zhang et al., 2024b).

The SH energy of MFC was studied in experimental models. The researchers described the effects of voltage, temperature, shunt capacitance, film thickness, and interlayer pressure (Yan and Huang, 2024). The results showed that the SH energy increases by 58.59% with increasing voltage in the range of 950-1150 V. In the range of 30–90 °C, the SH energy decreases by 36.08% with increasing temperature. In the range of 10–160 μF, the parallel capacitance has little effect on the SH energy. In the range of 6-10 -μm, the SH energy increases by 246% with increasing film thickness. In the range of 20800 kPa, the SH energy decreases by 47.11% with increasing interlayer pressure (Yan and Huang, 2024).

It was found in the experimental model that harmonic components have a significant effect on the characteristics of the SH MFC. As the harmonic component of the applied voltage increases, the SH breakdown voltage decreases. The shapes and sizes of the SH regions are different in different areas of the bilayer films, which is closely related to the local surface resistances of the film and the metal deposition of the breakdown sites. In addition, the SH breakdown occurs in a wide range of applied voltage, and the breakdown field strength decreases with an increase in the second harmonic component (Zheng et al., 2022).

Experiments with PPMFC have shown that the characteristics of the SH depend on temperature, voltage and pressure. The optimum temperature for the SH varies in the range of 20-70 -° C. With increasing voltage, the peak current of the SH also increases. And high pressure between the PPMFC layers stabilizes these characteristics. The SH model successfully predicts the waveform of the process. To improve the reliability of capacitors, it is necessary to control the dielectric resistance and take into account the system capacitance (Wu et al., 2024c).

The main characteristics of the SH of commercial capacitors with PET and PP -films were investigated at temperatures from -40 to +100 °C. It was found that the dielectric strength is inversely proportional to temperature for both types of capacitors. The average SH energy is from 50 mJ (100 °C) to 100 mJ (-40 °C) for PET capacitors and from 100 mJ (100 °C) to 500 mJ (-40 °C) for PP capacitors. The cumulative failure energy values for capacitors with PET films were found to exceed those for capacitors with PP films up to 100 °C. The dependences of the relative capacitance, C/C_0, and relative dielectric losses, δ/δ_0, at a frequency of 1 kHz were also obtained over a wide temperature range .

An increase in temperature significantly accelerates the degradation of insulation in PP films used in capacitors (Fan et al., 2023). As the temperature increases, the breakdown voltage decreases, the time until the first discharge occurs decreases, and the number and intensity of partial discharges increase. Temperature has the most pronounced effect on the discharge amplitude in the ascending part of the pulse, where non-monotonic changes are observed with maxima at 55 °C and 85 °C. These effects are easily explained by the intensification of the processes of thermal field emission of electrons during heating of the dielectric (Fan et al., 2023).

Conclusions

This review is the first comprehensive guide for electrical engineers characterizing the specifics of the SH phenomenon in MFC. Macroscopic and microscopic SH descriptors, such as temperature, pressure, SH energy, band gap, and electrical conductivity, are combined into a single picture. All factors known as of 2024 that significantly affect the possibility and quality of SH are discussed. The role of the initial elemental composition of the dielectric in the development of a material most susceptible to SH is clearly formulated.

The analysis of the latest literature sources together with the authors' research in the field of SH MFC allows us to identify two fundamental molecular phenomena - the formation of volatile products from polymer atoms and the electrical conductivity of the solid polymer residue (soot) - behind high-quality self-healing. The chemical composition of the polymer that supports the formation of gases plays a primary role. Gases are not only unable to conduct electricity, but also proportionally reduce the volume of solid soot remaining after the breakdown of the MFC. Small volumes of soot also cannot conduct electricity, since the probability of their formation of bridges between metal electrodes is marginal. If the volume of formed soot in the case of some chemical compositions of MFC is still significant enough, the quality of the SH will depend on the electrical conductivity of the soot samples obtained. In this context, poorly conducting samples are superior to samples with higher electrical conductivity values. Thus, we have formulated a specific procedure for the development of dielectrics supporting SH. The developed procedure is fully feasible in practice using the author's method of molecular modeling.

The field of self-healing capacitors is steadily advancing. Current research is aimed at improving their performance, expanding their application areas, and exploring the possibility of new self-healing mechanisms. Researchers are exploring new dielectric and electrode materials that exhibit improved self-healing properties, such as polymers with higher recovery rates, liquid metals with improved migration characteristics, and ceramics with higher breakdown strength. Efforts are focused on increasing the efficiency of self-healing mechanisms, reducing the energy required to isolate faults, and minimizing the impact on capacitance.

Integrating sensors and control systems into capacitors can provide intelligent SR, where the capacitor can detect and respond to breakdown events autonomously, further increasing their reliability and service life. Self-healing IPCs represent a significant advance in capacitor technology. They stand out for their increased reliability, durability and performance compared to foil capacitors. The ability to SR damage from electrical breakdown greatly expands their application in power electronics, automotive electronics, and renewable energy systems. Current R & D initiatives are focused on developing new materials, improving SR efficiency and integrating intelligent functions.

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