Energy Storage and Conversion 2025, 3(2), 2945.
https://doi.org/10.59400/esc2945

Review

Self-healing metalized film capacitors: Quo Vadis?

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CITATION

Andreeva NA, Chaban VV. Self-healing metalized film capacitors: Quo Vadis?. Energy Storage and Conversion. 2025; 3(2): 2945. https://doi.org/10.59400/esc2945

ARTICLE INFO

Received: 16 March 2025
Accepted: 18 April 2025
Available online: 28 May 2025

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 is the use of self-healing capacitors. The self-healing phenomenon significantly increases the service life of the device. This review presents a comprehensive analysis of the currently known aspects and mechanisms of self-healing in metal film capacitors. The role of the self-healing phenomenon in increasing the number of operating cycles of a dielectric capacitor is discussed. The molecular processes underlying significantly different self-healing potentials of dielectric polymers are verified. The review is addressed to specialists in electrical engineering.

Keywords: dielectric 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, plates) separated by an insulating material called a dielectric (**Figure 1**). The capacitance, C, of a capacitor, which numerically determines its ability to store energy, is directly proportional to the permittivity ε of the material and the area A of the plates and inversely proportional to the distance between them [1]:

$$C = \frac{\varepsilon \varepsilon_0 A}{d},$$

where ε_0 is the vacuum permittivity.

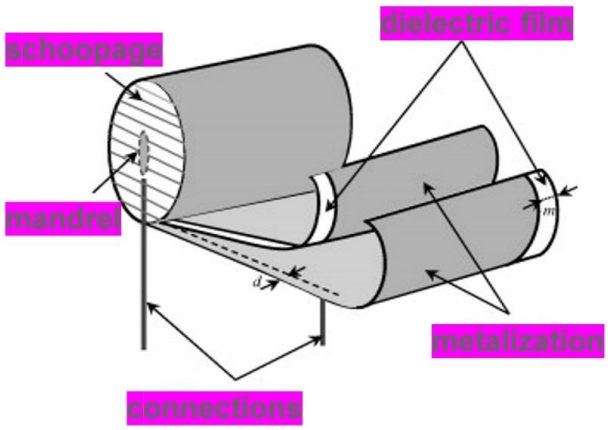

Figure 1. Construction of a metalized film capacitor [2].

Nowadays, there are two main types of dielectric capacitors—foil and metallized ones. 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), separated by a dielectric. Such capacitors have a stable high capacity. The thickness of the foil in foil capacitors is 5–9 micrometers. Foil electrodes do not evaporate during breakdown. In case of breakdown of the dielectric, an electric arc occurs between the plates, which leads to local heating and damage to the dielectric. Metal electrodes (foil) have high thermal conductivity and mechanical strength, so they do not evaporate or are not destroyed locally. 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 [3].

In metalized or metal-film capacitors (MFC), the plates are applied as a thin metal layer directly to the dielectric. Aluminum or zinc, or more often a combination of both, are used as electrodes, the thickness of which varies from 5 nm to 30 nm. Due to the extremely thin metalized layer, conventional mechanical methods cannot directly measure its resistivity. Instead, an indirect method is employed—measuring square resistance, expressed in ohms per square (Ω/sq) [3]. 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 gap is formed in the conductive layer, which prevents a short circuit. This allows the capacitor to almost completely restore its operational properties after minor overloads. This phenomenon is called self-healing (SH) of the capacitor.

The aluminum-zinc (Al-Zn) ratio critically influences both the SH efficiency and the square resistance of the film. Zinc-dominated coatings excel in SH due to the low evaporation temperature of zinc, enabling rapid isolation of defects. However, pure Zn suffers from poor oxidation resistance, reducing shelf life. Aluminum-rich layers offer lower square resistance (1–2 Ω/sq) and better stability but require higher energy for SH, compromising recovery performance. Zn-Al alloys (typically, 2%–10% Al) balance these properties. Al enhances environmental stability and current-carrying capacity (reducing square resistance at edges to 3–4 Ω/sq). Zn preserves SH capability, with the self-healing energy inversely proportional to square resistance [3].

SH MFC offers several significant advantages that make them indispensable in modern electronics. Their key benefit is the SH mechanism, where a local dielectric breakdown causes the thin metalized layer to vaporize around the fault, isolating the defect and allowing the capacitor to continue functioning. This dramatically improves reliability and lifespan compared to traditional foil capacitors, which fail completely upon dielectric breakdown. They are also more cost-effective to manufacture, as their simpler single-layer construction allows for automated high-speed production. Other advantages include non-inductive characteristics due to sprayed end connections and a tendency to fail in an open-circuit mode rather than short-circuit, which enhances system safety [3]. However, thin metal layers can be less stable than foil, which can lead to some changes in capacitance over time or with temperature changes. In addition,

due to the thinness of the metal layers, metalized capacitors can have a higher leakage current.

MFCs play a critical role in modern energy storage systems. Their ability to store and release energy efficiently makes them indispensable in applications requiring high power density and rapid energy discharge. For instance, in renewable energy systems, MFCs are used to smooth out fluctuations in power generation, ensuring a stable energy supply. Their compact size and high capacitance make them ideal for integration into solar inverters and wind turbine systems, where space and weight are often limiting factors.

In electric vehicles, MFCs are essential for energy management and power delivery. They are used in regenerative braking systems, where they temporarily store energy generated during braking and release it during acceleration. This not only improves the energy efficiency of electric vehicles but also extends the lifespan of the main battery system. Additionally, MFCs are employed in power electronics for fast charging stations, where they help manage high power loads and ensure reliable operation.

The self-healing properties of MFCs further enhance their suitability for energy storage applications. In systems where capacitors are subjected to frequent charge-discharge cycles, such as in grid energy storage or industrial power supplies, the ability to recover from electrical breakdowns significantly reduces maintenance costs and downtime. This makes MFCs a cost-effective and reliable solution for long-term energy storage, contributing to the overall efficiency and sustainability of modern energy systems.

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. The accumulation of electrical breakdowns eventually 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 partial thermal stress [2].

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. Metalized film capacitors are well suited for high-frequency and high-voltage electric fields found in electric vehicles, aerospace applications, and pulsed power systems due to their self-healing properties [4–8].

In this paper, we provide a comprehensive and systematic review of the latest scientific literature on MFCs and SH processes, integrating macroscopic engineering perspectives with microscopic material-level insights. For the first time in review publications on this topic, we bridge the gap between empirical observations (e.g., breakdown voltage, SH energy) and underlying molecular mechanisms, such as soot formation from evaporated electrodes and dielectric polymers. By analyzing the chemical composition of soot, volatile by-products, and the electrical conductivity of residues, we establish a unified framework to evaluate SH efficiency. This review not only catalogs existing knowledge but also identifies critical gaps—such as the trade-

offs between dielectric stability and self-healing propensity—and proposes actionable directions for future research. For instance, we highlight the potential of hydrogen-rich polymers to enhance gas formation during SH, thereby reducing conductive soot bridges, and advocate for computational tools (e.g., reactive molecular dynamics) to accelerate the design of next-generation dielectrics. Our synthesis of experimental and theoretical findings offers a roadmap for optimizing MFCs, emphasizing material innovation (e.g., aromatics-free polymers) and operational parameters (e.g., interlayer pressure, harmonic suppression) to advance reliability in high-stress applications like electric vehicles and renewable energy systems.

2. Mechanisms of self-healing in MFC

The phenomenon of SH in dielectric capacitors typically involves the evaporation of the electrode 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 (**Figure 2**) depending on the materials and design of the capacitor [9,10].

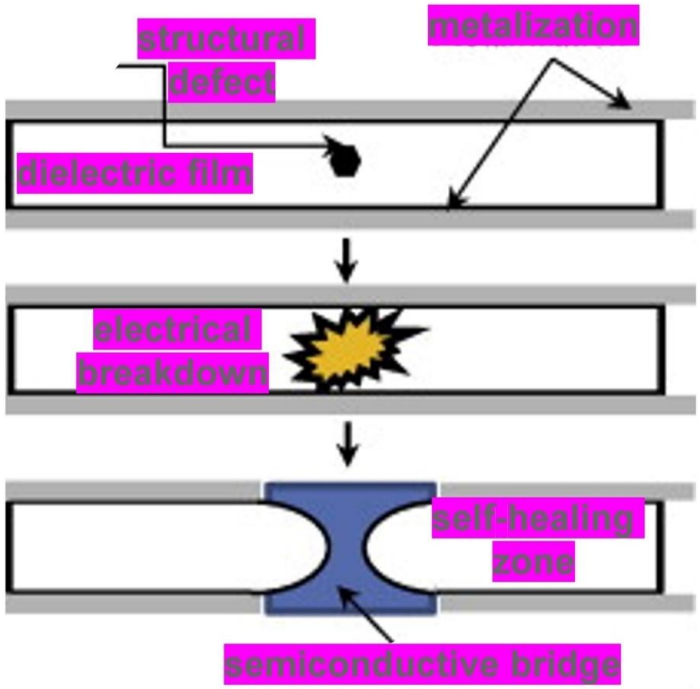

Figure 2. The phenomenon of self-healing in metallized film capacitors [2].

In capacitors with thin metalized electrodes, electrical breakdown generates a large amount of heat, causing the metalized layer near the defect to evaporate. This evaporation creates a gap in the electrode, isolating the defect and preventing further current flow [11]. 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 the 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 area in the form of a soot ("carbonized") layer. The resulting soot can form a semiconductor channel between the electrodes 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 [12]. Gaseous products do not conduct electric current, i.e., they additionally insulate the capacitor electrodes from each other, unlike solid soot.

Experiments show that the thickness of the dielectric layer harms the quality of the SH. The winding tension force during 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 area. This is 5% of the dielectric layer thickness of 5.8 μm. In addition, the size of the "carbonized" area in the dielectric exceeds the size of the evaporated area in the metalized layer by one and a half times [13].

3. Criteria and reasons for MFC failure

There are two types of MFC failure: 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 up to 10%) or an increase in the dielectric loss factor by two times. In turn, in the event of a catastrophic failure, a short circuit of the MFC or an open circuit occurs [14,15].

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 metalized film burns out, and, therefore, the area of the metallization zone decreases. This effect is cumulative. As a result of the operation, the capacity of the MFC decreases monotonically [16,17].

Some dielectric materials exhibit low potential for 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. Polyphenylene sulfide (PPS) and polyimide (PI) exhibit the lowest affinity for SH [18]. 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 more than 3000 K occurs at the defect site as a result of which part of the polymer and metal burns 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, a loss of mechanical strength of the MFC elements may occur—delamination or rupture of the metalized film. Pressure above critical can lead to the destruction of the capacitor housing and its irreversible failure.

After the SH, a layer of soot is formed at the breakdown site. If the soot channel accidentally short-circuits the capacitor plates, then 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 [19]:

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

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 compared to f = 0.5 for PP. The higher the f index, the weaker the ability to SH [20,21]. The reader's attention should be drawn separately to the conventionality of the definitions of "volatile elements" and "non-volatile elements". For example, "non-volatile elements"—carbon, nitrogen, and sulfur—can also generally form volatile compounds. However, 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 failure of the MFC may be: (1) chemical corrosion of the capacitor due to humidity, (2) electrochemical corrosion, and (3) overheating and melting of the dielectric film [22]. Atmospheric corrosion significantly reduces the service life of MFCs. 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 anti-corrosion properties of MFCs. 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 [23–25].

4. Properties of self-healing

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, and the probability of breakdown at a given voltage [26].

The SH energy in the MFC is the amount of energy required to restore the insulating layer 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 dielectric and electrode, 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 metalized electrodes of the MFC. A lower SH energy implies a smaller evaporated area, lower capacity losses, and a longer service life of the device [27,28].

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 energy levels, < 100 mJ, the peel stress on metallized films remains below 8

N/m, while dangerous energies, > 250 mJ, lead to an increase in peel stress to 14 N/m [29].

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 gradients. Changes in these parameters can indicate the occurrence and quality of SH [30].

Microscopy techniques such as scanning electron microscopy and transmission electron microscopy can be used to visualize the breakdown location and characterize the SH [13]. These techniques reveal the morphology of the electrode and dielectric materials, which provides insight into the SH mechanisms [31]. Accelerated aging methods are often used to evaluate SH efficiency. When the 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 [32].

Wu et al. [13] concluded that the SH process in metalized films does not lead to the formation of polar fragments in the dielectric layer, as confirmed by Fourier-transform infrared spectroscopy (FTIR). This conclusion is based on the comprehensive analysis of experimental data obtained under strictly controlled conditions. During the experiments, metalized PP films underwent SH when subjected to 3 kV voltage in a vacuum (10 Pa), which eliminated the influence of atmospheric oxygen.

FTIR analysis showed no characteristic absorption bands for polar groups (such as OH in the 3550–3750 cm^{-1} range or C=O around 1700 cm^{-1}), indicating a non-oxidative nature of the process. Only a slight reduction in intensity was observed for the -CH_3 group bands (1350–1500 cm^{-1}), suggesting PP chain scission without the formation of polar fragments. These findings are consistent with gas chromatography results, which detected incomplete combustion products (C_2H_2, C_2H_6, CO, H_2) but no traces of polar oxygen-containing compounds [13].

Additional studies using scanning electron microscopy (SEM) and *X*-ray photoelectron spectroscopy (XPS) confirmed the absence of metal oxides in the SH zone, revealing primarily dielectric carbonization and metal layer evaporation processes. Thus, the combination of FTIR with other analytical methods provided conclusive evidence that the SH mechanism in metalized films fundamentally differs from thermal aging, as it proceeds without forming polar fragments in the dielectric layer. The integrated experimental approach clearly demonstrates that while SH involves intense thermal effects and material transformations, it does not induce oxidative degradation pathways characteristic of other aging processes [13].

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 [33]. 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 [34].

Finite element calculations help to obtain the characteristics of the electric field distribution in a metal electrode [35]. The simulation shows that a hole in the electrode causes a change in the direction of the current. The concentration of the current occurs at the upper or lower edge of the hole, which leads to a higher current density and power density in this region than in other regions [36]. Also, using the finite element method, the interruption of the filamentary breakdown current was modeled, when a thermally induced increase in the series resistance in the metallization of the electrodes destabilizes the plasma breakdown arc [37].

One of the parameters characterizing the SH is the value of cumulative energy. The SH energy in a capacitor can be expressed as follows [38]:

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

Here k—is a coefficient, V is a working voltage, C is a capacity of the tested capacitor, R_s is a surface resistance of the metalized film, $\alpha(P)$ is 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 its molecular structure. Using the method of classical molecular dynamics, the interaction of new dielectric liquids based on dialkyl carbonates with the polymer films most often used in MFCs—PP, PET, and cellulose—was investigated. 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 [39]. The compatibility of various impregnating liquids with various polymers is based on the intermolecular forces of interaction between the dielectric and the liquid, the pore sizes in the dielectric material, and the flexibility of the impregnating liquid molecules (**Figure 3**). The studied organic carbonates were recommended for use in new-generation capacitor technologies instead of mineral oils.

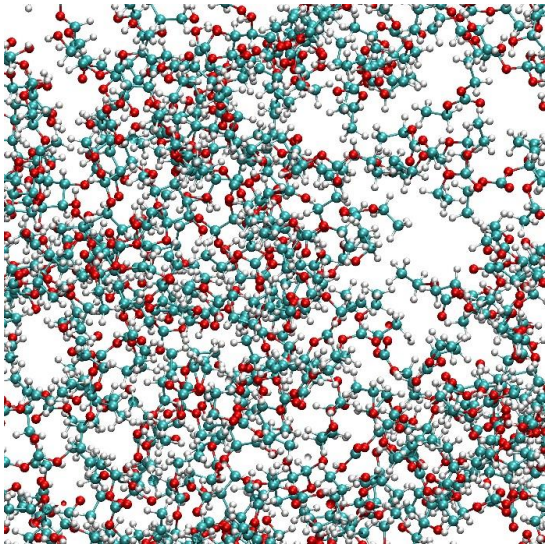

Figure 3. Spatial distribution of liquid diethyl carbonate molecules over the volume of a solid dielectric (cellulose) during equilibrium modeling using classical molecular dynamics.

Note: The instantaneous molecular configuration of the material at 298 K is shown. Carbon atoms are blue, oxygen atoms are red, and hydrogen atoms are white.

Using the kinetic energy injection method [40–43], adapted to the study of high-temperature chemical reactions, it is possible to study the potential energy surface to predict the chemical composition of soot samples 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, band gap, and infrared vibrational spectra (**Figure 4**) using the methods of density functional theory. We draw attention to the fact that in the above calculations, 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.

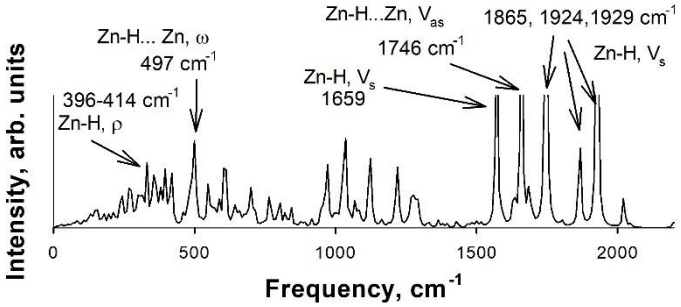

Figure 4. Vibrational spectra of the soot sample in the mid-infrared and far-infrared region in the system of chemical composition Zn (electrode) + PP (dielectric).
Note: Calculations were carried out using the density functional theory method—M11/6-31 G* for carbon and hydrogen atoms and the LANL2DZ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

The chemical composition and amount of gas products formed after electrical breakdown fundamentally affect the SH. Gas products have tiny electrical conductivity, so their molar fraction is directly proportional to the SH quality. Moreover, gas formation obviously reduces the volume of non-gasified 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 us 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 the 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 [12].

In the case of polymer insulators, when 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 in order to adequately represent the electronic structure of a macroscopic-sized soot sample, and a second-generation density functional, for example, PBE [44]. In this case, the periodic chemical structure for calculating the electrical conductivity (**Figure**

5) must be based on the microscopic configuration of the calculated global minimum or another accessible, sufficiently low-energy structure that convincingly represents the soot sample of the destroyed dielectric.

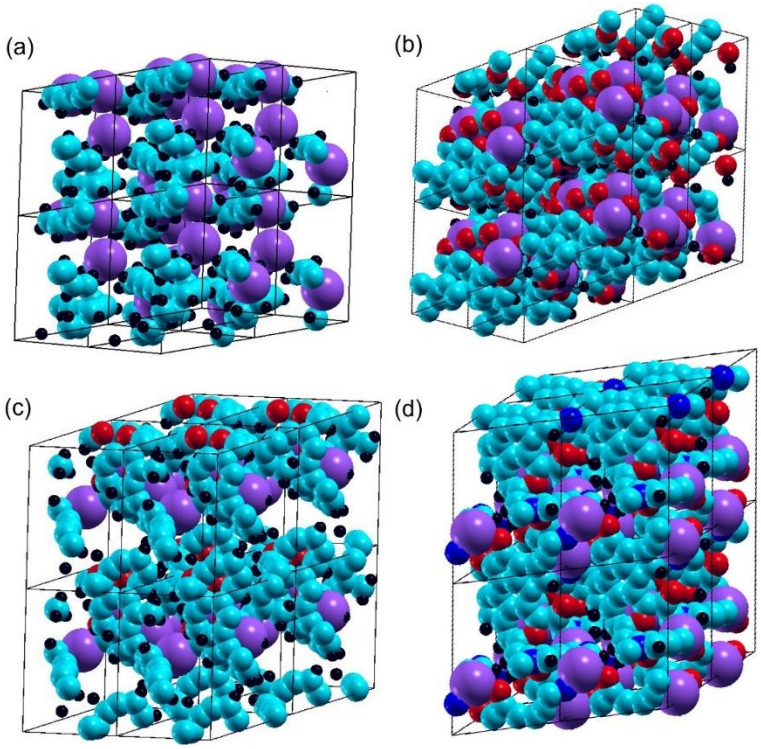

Figure 5. Periodic structures in soot samples obtained for the following systems: **(a)** 4 Zn + PP; **(b)** 4 Zn + PET; **(c)** 4 Zn + PC; **(d)** 4 Zn + Kapton.

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

Machine learning models become a demanded 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 can be used for advanced property prediction, microstructure recognition, experiment optimization, and performance monitoring [45–47].

5. Materials for metal film capacitors

The efficiency, reliability, and service life of capacitors depend on the correct choice of materials. Dielectric capacitors have the following advantages: high energy density, fast response to voltage changes, and long service life. These properties make them indispensable in power engineering and electronics, where high performance and reliability of components are required [48]. Some dielectric and electrode materials have already been investigated for their SH properties, but most remain too limitedly studied. Researchers and engineers need to understand the limits of SH capabilities

and ways to modify known dielectric materials to minimize the likelihood of forming semiconducting bridges connecting the electrodes of MFCs 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 alloys, 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 [49].

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% [49]. 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 (PPFCs). When a strong electric field is applied, the air is ionized and increases the area and duration of the SH process in PPFCs. Also, in segmented PPFCs, 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 five times by strengthening the winding, sealing the ends after the vacuum, optimizing heat treatment in the vacuum, and impregnating in the vacuum [28]. The capacity of PPFCs is lost faster with alternating applied voltage than with direct voltage [50,51].

Polymers such as polypropylene, polyethylene terephthalate, polyethylene naphthalate, polycarbonate, and polyphenylene sulfide have been widely used in self-healing capacitors [8,52,53], but expanding this list seems appropriate and beneficial. For example, Zhu et al. [54] evaluated the SH ability of metalized high-temperature dielectric films made of polyethylene-2,6-naphthalate, polyether ketone, and polyimide. It was found that high carbon content in PI leads to SH failure at low layer resistance, although it exhibits low SH energy at high layer resistance. The probability of high SH of metalized polyether ketone film is significantly reduced at high interlayer pressure. In addition, high SH energy is achieved in polyether ketone, which would lead to rapid aging of MFC [54]. In contrast, polyethylene 2,6-naphthalate with relatively low carbon content and an aliphatic-aromatic alternating structure exhibits excellent SH ability under various 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 [54].

In the work of Kao et al. [18], 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, and the dissipation factor of 0.281%–0.517% were recorded. Weibull breakdown strength of 347–674 MV m^{-1} was obtained [18].

Polymers for MFCs can be 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 post-breakdown SH efficiency due to their high carbon content. Chen et al. [55] investigated an aromatic-free polynorbornene copolymer that exhibits electrical conductivity two orders of magnitude lower than that of state-of-the-art polyetherimide at elevated temperatures and high electric fields due to its large band gap of about 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 a high discharge density of 3.73 J/cm and charge-discharge efficiency (95% at 150 ℃), surpassing 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 [55].

It has been established that capacitors with a PPS dielectric have an extremely low ability to SH. For each tested capacitor, no more than five 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 formed as a result of the electrical breakdown of this polymer film at the molecular level [43].

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 [56] 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 was achieved in a composite containing 0.3% PEI at 100 ℃ [56]. Reducing the cost of production of this and similar materials could allow them to be introduced into mass production.

6. Influence of external factors

The efficiency of the SH process can significantly depend on thermodynamic conditions. 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 for optimizing the operating conditions of capacitors and developing new materials with improved electrical characteristics. Experimental studies of SH in MFC have shown that the duration of the process and the time-dependent resistance of the micro-arc discharge are influenced by interlayer pressures typical for MFC. It was found that the insulation resistance of stacked metalized 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 a high-temperature arc discharge.

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. At the same time, at 900 kPa, most breakdowns occur at electric field strengths less than 200 V/μm [54]. In addition, high interlayer pressure in the MFC helps to reduce the capacity 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 metalized polypropylene film were studied at pressures of 20 kPa–1000 kPa. The breakdown field of the metallized film decreases significantly with increasing pressure in the system. Large energy losses at a strong electric field can be prevented by increasing the pressure. Therefore, increasing the pressure between the layers to a certain extent contributes to the reliability of the capacitor [57].

The energy of the SH MFC was studied on experimental models. The researchers described the influence of voltage, temperature, shunt capacitance, film thickness, and interlayer pressure [58]. The results showed that the SH energy increases by 58.59% with increasing voltage in the range of 950–1150 B. In the range of 30–90 °C, the energy of the SH decreases by 36.08% with increasing temperature. In the range of 10–160 μF, 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 20–800 kPa, the energy of the SH decreases by 47.11% with increasing interlayer pressure [58].

The experimental model showed 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 [59].

Experiments with MPPC 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. High pressure between the MFC 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 capacitance of the system [31].

The main SH characteristics of commercial PET and PP capacitors 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 ranges from 50 mJ (100 °C) to 100 mJ (−40 °C) for PET capacitors and from 100 mJ (100 °C) up to 500 mJ (−40 °C) for PP capacitors. Cumulative failure energy values for PET film capacitors were found to exceed those for PP film capacitors by up to 100 °C. The dependences of the relative capacitance, C/C_0, and the

relative dielectric losses, δ/δ_0, at a frequency of 1 kHz were also obtained over a wide temperature range [60].

Increasing temperature significantly accelerates insulation degradation in PP films used in capacitors [61]. 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 ℃ and 85 ℃. These effects are easily explained by the intensification of the processes of thermal field emission of electrons during the heating of the dielectric [61].

7. Conclusions

This review characterizes 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.

An analysis of the latest literature sources together with the authors' research in the field of self-healing of MFCs 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)—that are behind high-quality self-healing [43]. The chemical composition of the polymer, which supports abundant gas formation, plays a primary role. Gases are not only unable to conduct electricity but also proportionally reduce the volume of solid soot remaining after MFC breakdown. 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 MFCs is still significant enough, then the quality of self-healing will depend on the electrical conductivity of the obtained soot samples. 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 self-healing. The developed procedure is fully feasible in practice using the author's method of molecular modeling [43].

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. One investigates new dielectric and electrode materials that exhibit improved self-healing properties, such as polymers with higher recovery rates, 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 SH, where the capacitor can detect and respond to breakdown events autonomously, further increasing their reliability and service life. Self-healing MFCs represent a

significant advance in capacitor technology. They stand out for their increased reliability, durability, and performance compared to foil capacitors. The ability to SH after electrical breakdown greatly expands applications in power electronics, automotive electronics, and renewable energy systems. Current R&D initiatives are focused on developing new materials, improving SH efficiency, and integrating intelligent functions.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Conflict of interest: The authors declare no conflict of interest.

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