



A Review on Dielectric Breakdown of Anodic Oxide Films on Aluminum Alloys

Hien Van Pham^{a,b}, Cheolnam Yang^a and Sungmo Moon^{a,b,*}

^aEnergy & Environment Materials Research Division, Korea Institute of Materials Science, 797 Changwon-daero, Seongsan-gu, Changwon, Gyeongnam 51508, Korea

^bAdvanced Materials Engineering, Korea University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Korea

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Abstract

This paper reviews the dielectric breakdown resistance and behavior of anodic oxide films in air environment. It begins with a description of the dielectric breakdown mechanisms of dielectric materials. The paper then introduces different types of dielectric materials and compares them in terms of dielectric strength, thermal conductivity, mechanical strength and cost. Next, the paper summarizes various fabrication methods for dielectric aluminum oxide layers, discussing the advantages and disadvantages of each method. Finally, it provides an overview of current studies on the dielectric breakdown properties of anodic aluminum oxide films formed on different aluminum alloys in various electrolytes.

Keywords : Aluminum alloys; Anodic oxide film; Dielectric breakdown; Dielectric material.

1. Introduction

Aluminum alloys possess a combination of desirable properties, making them the materials of choice for many different industries, including automobiles, aerospace, machinery, kitchen tools, and semiconducting/display equipment [1-3]. Their high strength-to-weight ratio is particularly valuable in the automotive and aerospace industries, where weight reduction is crucial for reducing energy consumption and pollution. Their excellent electrical and thermal conductivities make them also suitable

for applications in electronic components and heat exchangers, where efficient heat dissipation and good electrical conduction are required. Aluminum alloys are non-toxic, making them safe for use in consumer products such as kitchen tools and food packaging. Aluminum alloys also demonstrate good formability and ductility, enabling the production of a wide range of products, from simple sheets to complex shapes. Their recyclability contributes to the sustainable use of resources and reduces the environmental impact of production [1-3].

Generally, a 2-3 nm thick aluminum oxide layer forms spontaneously on the surface of aluminum [4]. This native oxide layer has very high dielectric

*Corresponding Author : Sungmo Moon
Korea Institute of Materials Science
Tel.: +82 55 280 3549; Fax: +82 55 280 3645
Email : sungmo@kims.re.kr

strength, but it is relatively thin, thereby showing low resistance against dielectric breakdown under applied high electric field. The dielectric breakdown of the natural oxide layer allows electric current to pass through it, leading to damage of equipment and products, as well as safety risks to workers and users. Thus, the low dielectric breakdown resistance can limit the use of aluminum alloys in high voltage applications.

The resistance to dielectric breakdown of aluminum alloys can be improved by fabricating a thick dielectric layer on the aluminum surface. Various materials have been used for the dielectric layer, such as polytetrafluoroethylene, polyimide, aluminum oxide, silicon dioxide, yttrium oxide, silicon nitride and boron nitride. Amongst these, aluminum oxide is a widely used dielectric material due to its unique combination of good dielectric strength, thermal conductivity and mechanical strength.

Various methods have been used for fabrication of a dielectric aluminum oxide layer on the aluminum surface, such as atomic layer deposition (ALD) [5,6], chemical vapor deposition (CVD) [7], sol-gel coating [8,9], plasma spraying [10,11], anodizing [12-15] and plasma electrolytic oxidation (PEO) [16,17]. Amongst them, anodizing is often a preferred one owing to its simplicity, cost-effectiveness and eco-friendliness. Anodic aluminum oxide (AAO) film is formed on the aluminum surface by applying an anodic current in an electrolytic cell, during which the chemical reactions occur between Al^{3+} cations migrating outward from the aluminum substrate towards the electrolyte and O^{2-} , OH^- , and electrolyte anions migrating inward from the electrolyte towards the aluminum/oxide interface [12,18]. Growth behavior and dielectric breakdown of

the AAO film generally depend on the applied current density/voltage and their forms, electrolyte composition, alloying elements, temperature and anodizing time. A comprehensive understanding of the dielectric breakdown behaviors of the AAO films is necessary for the development of aluminum alloy components used in electric vehicles, semi-conducting and display industries.

In this paper, we review the dielectric breakdown mechanisms, the types of dielectric materials, and the fabrication methods of the dielectric aluminum oxide layer. Additionally, we summarize current studies on the dielectric breakdown of the AAO films formed on different aluminum alloys in various electrolytes.

2. Dielectric breakdown mechanism of dielectric materials

Dielectric breakdown is a phenomenon that occurs in the dielectric material when it is subjected to an electric field strength (E) that exceeds a critical value known as breakdown field strength (E_{bd}). This results in a loss of electrically insulating properties of the dielectric material, causing it to become conductive. This can significantly reduce performance of electrical components and equipment, compromise product quality, and pose safety risks to workers and users.

Fig. 1 illustrates the schematic of dielectric breakdown in a dielectric material subjected to an applied high electric field. The schematic depicts three stages: the initial stage, current leakage and dielectric breakdown:

- 1) Initial stage: When the electric field strength (E) is absent, there is no movement of charge carriers (electrons and ions)
- 2) Current leakage: When the electric field strength (E) is lower than the breakdown

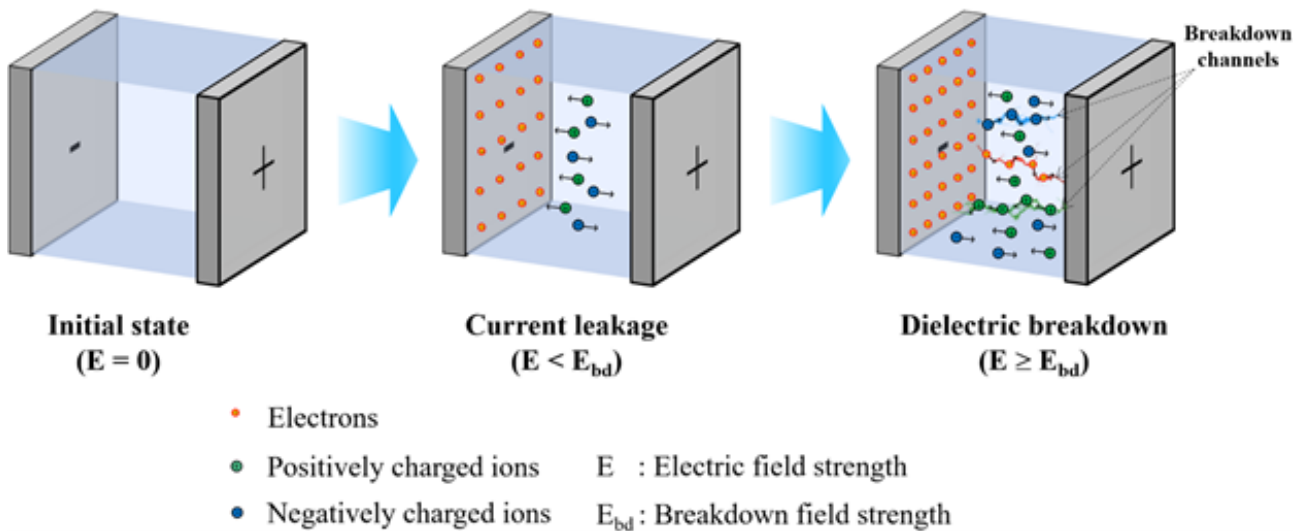


Fig. 1. Schematic representation of dielectric breakdown of a dielectric material.

field strength (E_{bd}) but still high enough, a small number of ions, move through the dielectric material under the electric field, while electrons can not move through the AAO film but accumulate on the dielectric material surface facing the negative electrode (cathode). As the electric field strength increases, the number of charge carriers moving through the material increases, leading to a gradual rise in leakage current. The insulating properties of the dielectric material degrade but are not completely lost.

- 3) Dielectric breakdown: When the electric field strength (E) reaches or exceeds the breakdown field strength (E_{bd}), a massive number of charge carriers, including electrons and ions, suddenly move through the dielectric material. The electric field concentrates locally at weak points in the dielectric material, resulting in the formation of breakdown channels. As charge carriers can easily flow through these breakdown channels, the dielectric material no longer maintains its insulating properties and becomes conductive.

The precise mechanism for dielectric breakdown of the dielectric material

has been debated. The first dielectric breakdown mechanism is electron avalanche breakdown, which was developed by von Hippel et al. [19-21], Fröhlich et al. [22,23] and O'Dwyer et al. [24]. Electron avalanche breakdown occurs when a high electric field generates free electrons within the dielectric material. These electrons are accelerated and collide with atoms or molecules, creating electron-ion pairs through impact ionization. This process repeats, causing an exponential increase in the number of free charge carriers, leading to a sudden increase in conductivity and a catastrophic failure of the dielectric material. Factors affecting this mechanism include the dielectric strength, thickness of the dielectric material, type and density of defects within the dielectric material.

Simultaneously with the development of electron avalanche breakdown mechanism, thermal breakdown was developed by Fock et al. [25], Moon et al. [26] and Wagner et al. [27]. Thermal breakdown occurs when heat generation exceeds heat dissipation within the dielectric material, leading to a localized increase in temperature. This locally increased temperature causes an exponential increase in the conductivity of the dielectric material. The increased conductivity allows more current to flow

through the dielectric material, leading to further heat generation. As the heat accumulates, a thermal runaway process can occur, ultimately resulting in the breakdown of the dielectric material. Key factors affecting this mechanism are the thermal conductivity of the dielectric material, type and density of defects in dielectric material, and ambient temperature.

Thirdly, electromechanical breakdown mechanism was developed by Stark et al [28] and Fothergill et al. [29]. When a dielectric material is subjected to a high electric field, mechanical stress is induced. If the strain energy released by the electric stress exceeds the strain energy required for material deformation, mechanical cracks within the dielectric material will be initiated. These cracks act as weak points where the electric field locally concentrates, leading to dielectric breakdown. Factors affecting this mechanism include thickness of the dielectric material, type and density of defects within the dielectric material, dielectric strength of the dielectric material and ambient temperature.

Other dielectric breakdown mechanisms include partial discharge breakdown and free volume dielectric breakdown [30]. In the partial discharge breakdown mechanism, the electric field concentrates locally at voids and/or cavities present in the dielectric material. This leads to electrical discharges through the voids and/or cavities, causing deterioration of the dielectric material. On the other hand, in the free volume breakdown mechanism, the electric field accelerates charge carriers to move through free volume spaces in low density amorphous regions, triggering an electron avalanche breakdown. Factors affecting both the mechanisms include the number and size of voids, cavities or other free volume spaces in the dielectric

material, dielectric strength, and ambient temperature.

It is important to note that the dielectric breakdown is susceptible to humidity in environments. The dielectric materials may absorb moisture from the humid environment, creating conductive pathways for charge carriers and potentially leading to dielectric breakdown at lower applied voltage. Additionally, exposure to the moisture can cause physical and chemical degradations of the dielectric material, further reducing its dielectric breakdown resistance.

3. Types of dielectric materials

Many dielectric materials have been used for industrial applications, including polymers (such as polytetrafluoroethylene and polyimide) and ceramics (such as aluminum oxide, silicon dioxide, yttrium oxide, silicon nitride, and boron nitride). Table 1 displays the characteristics of these dielectric materials in terms of dielectric strength, thermal conductivity and mechanical strength.

Aluminum oxide is widely used as a dielectric material for high voltage applications due to its combination of relatively high dielectric strength, good thermal conductivity, excellent mechanical strength and low cost. Aluminum oxide has a dielectric strength ranging from 16.7 to 17.7 $\text{kV}\cdot\text{mm}^{-1}$, which is lower than that of polytetrafluoroethylene (60-173 $\text{kV}\cdot\text{mm}^{-1}$), polyimide (22-470 $\text{kV}\cdot\text{mm}^{-1}$) and boron nitride (37-74 $\text{kV}\cdot\text{mm}^{-1}$), and comparable to that of yttrium oxide (11.6-17.3 $\text{kV}\cdot\text{mm}^{-1}$) and silicon nitride (10-20 $\text{kV}\cdot\text{mm}^{-1}$).

As can be seen in Table 1, aluminum oxide has good thermal conductivity, ranging from 30 to 40 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, which is much higher than that of polymers (0.10-0.35 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and yttrium oxide (12.8-13.6 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). The

Table 1. Characteristics of dielectric materials.

Type of dielectric material	Dielectric strength ($\text{kV}\cdot\text{mm}^{-1}$)	Thermal conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Mechanical strength	Cost ($\text{\$}\cdot\text{kg}^{-1}$)
Polytetrafluoroethylene (PTFE)	60-173	0.25-0.30	Low	7.26-20.68
Polyimide (PI)	22-470	0.10-0.35	Low to moderate	48.60-780
Yttrium oxide (Y_2O_3)	11.6-17.3	12.8-13.6	Moderate	7-35
Aluminum oxide (Al_2O_3)	16.7-17.7	30-40	High	0.35-0.49
Silicon nitride (Si_3N_4)	10-20	10-43	High	39-76
Boron nitride (BN)	37-74	20-60	Moderate to high	28-150

thermal conductivity of aluminum oxide is comparable with those of silicon nitride ($10\text{-}43 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) and boron nitride ($20\text{-}60 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). The good thermal conductivity allows aluminum oxide to prevent thermal breakdown. Additionally, aluminum oxide exhibits better mechanical strength than polymers and yttrium oxide. The mechanical strength of aluminum oxide is comparable to those of silicon nitride and boron nitride. The high mechanical strength enables aluminum oxide to maintain its structural integrity and insulating properties when subjected to electromechanical stress under applied high electric field.

Aluminum oxide has the lowest cost among the dielectric materials listed in Table 1, ranging from 0.35 to 0.49 $\text{\$}\cdot\text{kg}^{-1}$. The cost of aluminum oxide is much lower than those of silicon nitride, boron nitride and polyimide and also lower than those of polytetrafluoroethylene and yttrium oxide.

4. Fabrication methods for dielectric aluminum oxide layers

The dielectric aluminum oxide layer can be formed on the aluminum surface by various methods, including ALD, CVD, sol-gel coating, plasma spraying, anodizing and PEO [5-17]. Table 2 summarizes the advantages and disadvantages of these fabrication methods.

ALD and CVD provide high-purity

aluminum oxide layers with good adhesion, highly uniform and precisely controlled thickness. However, these methods have several limitations, such as slow deposition rates, and the need for specialized equipment. Additionally, the layer formed by ALD is typically limited to nanometer-scale thicknesses and CVD can produce layers up to several micrometers.

Sol-gel coating offers a relatively pure aluminum oxide layer at a low cost. However, this method is complex and requires heat treatment after coating. Plasma spraying is capable of producing a desirable thickness more than several hundred micrometers and high hardness coating, but it requires specialized coating equipment, and the plasma-sprayed coating suffers from low adhesion, high porosity and non-uniform thickness. Poor adhesion of plasma-sprayed coating can be attributed to its mechanical bonding, depending on the surface morphology and roughness, making it susceptible to delamination or spalling under certain conditions. The high porosity of the plasma-sprayed coating arises from pores and cracks formed by the inclusion of unmelted particles and solidified shrinkage of melted liquid. The high porosity negatively affects its dielectric breakdown resistance. PEO method shares advantages with anodizing, including its simple process, high thickness, and good adhesion of the PEO film. However, the PEO film has high porosity and surface roughness.

It is important to note that ALD, CVD,

Table 2. Advantages and disadvantages of various fabrication methods for dielectric aluminum oxide layer.

Method	Advantages	Disadvantages
Atomic layer deposition	<ul style="list-style-type: none"> • High-purity aluminum oxide layer • Highly uniform thickness • Precisely controlled thickness • Good adhesion 	<ul style="list-style-type: none"> • Slow deposition rate • Requires specialized equipment • Limited thickness • (typically nanometer scale) • High cost
Chemical vapor deposition	<ul style="list-style-type: none"> • High-purity aluminum oxide layer • Highly uniform thickness • Precisely controlled thickness • Good adhesion 	<ul style="list-style-type: none"> • Relatively slow deposition rate • High processing temperature • Requires specialized equipment • Limited thickness • (typically several microns) • High cost
Sol-gel coating	<ul style="list-style-type: none"> • Relatively pure aluminum oxide layers • Low cost 	<ul style="list-style-type: none"> • Complex process • Requires heat-treatment
Plasma spraying	<ul style="list-style-type: none"> • High thickness • High hardness 	<ul style="list-style-type: none"> • High processing temperature • Low adhesion • High porosity • Non-uniform thickness • Requires specialized equipment • High cost
Plasma electrolytic oxidation	<ul style="list-style-type: none"> • High thickness • High hardness • Good adhesion • Simple process 	<ul style="list-style-type: none"> • High porosity • Non-uniform thickness • Requires sealing treatment • High cost
Anodizing	<ul style="list-style-type: none"> • Uniform thickness • Easy thickness control • Relatively high thickness • Good adhesion • Simple process • Low cost 	<ul style="list-style-type: none"> • Requires sealing treatment

plasma spraying and PEO are of high cost. The high cost of these methods can be attributed to several factors, such as the need for specialized equipment, high energy consumption, and the use of expensive precursors or raw materials. Additionally, the slow deposition rates associated with ALD and CVD can increase the overall processing time and cost.

Anodizing stands out as a better choice for fabricating dielectric aluminum oxide layer compared to other methods for several reasons:

- 1) Precise control of film thickness: Anodizing allows for precise control in the AAO film thickness by adjusting the anodizing conditions. This results in a highly uniform AAO film in thickness across the entire surface of the aluminum component.
- 2) Strong adhesion: The AAO film is grown

from the aluminum substrate itself, forming a strong, integral bond with the aluminum substrate. This leads to excellent adhesion between the AAO film and the aluminum substrate.

- 3) Cost-effectiveness: Anodizing is a cost-effective process compared to other methods. This is due to its simple process, which requires less specialized equipment, low cost of equipment and electrolyte, and low energy consumption.

5. Current studies on dielectric breakdown of anodic aluminum oxide films

Table 3 shows the dielectric breakdown voltages of the AAO films formed on pure aluminum and different aluminum alloys in various anodizing electrolytes, reported in

Table 3. Dielectric breakdown voltage of the AAO films formed on pure aluminum and different aluminum alloys in different electrolytes, reported in the literature from 2015 to 2024.

Type of Al alloy	Electrolyte	Anodizing condition	Post-treatment	AAO film thickness / μm	Dielectric breakdown voltage /kV	Year	Refs.
AA6061	152.8 g/L H_2SO_4	10 $\text{mA}\cdot\text{cm}^{-2}$ or 21 ~ 32 V, 0 $^\circ\text{C}$	Boiling water (BW) sealing, 100 $^\circ\text{C}$, 0 ~ 60 min	47	0.6 ~ 0.9	2015	[31]
AA6061	126 ml H_2SO_4 in 1374 ml DI water	20 V, 0 ~ 20 $^\circ\text{C}$	-	0.1 ~ 0.7	0.3 ~ 1.7	2018	[32]
AA6061	1.5 M H_2SO_4	20 V, 20 $^\circ\text{C}$	-	30 ~ 60	0.9 ~ 2.0	2019	[33]
AA6061	1.5 M H_2SO_4 + 1 ~ 4 mM $\text{Ce}(\text{SO}_4)_2$	20 V, 15 $^\circ\text{C}$	-	24 ~ 30	0.6 ~ 1.0	2020	[34]
AA5052	3 wt.% $\text{C}_2\text{H}_2\text{O}_4$	15 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, 15 $^\circ\text{C}$	Sealing in BW without and with additives, 90 ~ 95 $^\circ\text{C}$, 30 min	30	1.9 ~ 3.4	2020	[35]
AA6061					2.0 ~ 2.8		
AA6061	9.5 M $\text{C}_6\text{H}_{18}\text{O}_{24}\text{P}_6$	80 V, 0 ~ 20 $^\circ\text{C}$	-	5 ~ 30	0.3 ~ 0.8	2021	[36]
AA5052	15 vol.% H_2SO_4	10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, -3 $^\circ\text{C}$	Sealing in BW + 1% Oxidite S-54 + 1% sodium lauryl sulfate, 85 ~ 95 $^\circ\text{C}$, 35 min	50	2.5	2021	[37]
	3.5 wt.% $\text{C}_2\text{H}_2\text{O}_4$	10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, 15 $^\circ\text{C}$			3.9		
	1 st step: 15 vol.% H_2SO_4 2 nd step: 3.5 wt.% $\text{C}_2\text{H}_2\text{O}_4$	1 st step: 10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, -3 $^\circ\text{C}$ 2 nd step: 10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, 15 $^\circ\text{C}$			2.2 ~ 3.3		
AA6061	15 vol.% H_2SO_4	10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, -3 $^\circ\text{C}$	Sealing in BW + 1% Oxidite S-54 + 1% sodium lauryl sulfate, 95 ~ 100 $^\circ\text{C}$, 30 min	50	1.7	2021	[37]
	3.5 wt.% $\text{C}_2\text{H}_2\text{O}_4$	10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, 15 $^\circ\text{C}$			3.2		
	1 st step: 15 vol.% H_2SO_4 2 nd step: 3.5 wt.% $\text{C}_2\text{H}_2\text{O}_4$	1 st step: 10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, -3 $^\circ\text{C}$ 2 nd step: 10 ~ 30 $\text{mA}\cdot\text{cm}^{-2}$, 15 $^\circ\text{C}$			2.2 ~ 2.6		
Pure Al	5 ~ 20 vol.% H_2SO_4	40 $\text{mA}\cdot\text{cm}^{-2}$, 15 $^\circ\text{C}$	-	5 ~ 60	0.2 ~ 2.0	2023	[18]
	2 ~ 8 wt.% $\text{C}_2\text{H}_2\text{O}_4$				0.4 ~ 2.4		
AA6061	20 vol.% H_2SO_4	10 $\text{mA}\cdot\text{cm}^{-2}$ or 10 to 5.5 $\text{mA}\cdot\text{cm}^{-2}$, 2 $^\circ\text{C}$	-	50	2.5 ~ 2.9	2024	[38]
	8 vol.% H_2SO_4 + 3 wt.% $\text{C}_2\text{H}_2\text{O}_4$				3.4 ~ 3.9		

the literatures from 2015 to 2024. The table includes data for pure aluminum and two aluminum alloys, AA6061 and AA5052. The dielectric breakdown voltage values for the AAO films formed on pure aluminum ranged from 0.2 to 2.0 kV for film thicknesses of 5 to 60 μm . In contrast, those formed on AA6061 ranged from 0.3 to 3.9 kV for film thicknesses from 0.1 to 60 μm , and those formed on AA5052 ranged from 1.9 to 3.9 kV for film thicknesses of 30 to 50 μm . This reveals that the dielectric breakdown resistances of the AAO films formed on AA5052 and AA6061 are similar and they are higher than those on pure aluminum.

In general, the dielectric breakdown resistance of the AAO films formed in oxalic acid electrolyte is higher than that obtained in sulfuric acid electrolyte for both pure

aluminum and aluminum alloys. The AAO films formed in sulfuric acid electrolyte showed dielectric breakdown voltage values ranging from 0.2 to 2.9 kV for film thicknesses of 0.1 to 60 μm , while those formed in oxalic acid electrolyte exhibited higher values, ranging from 0.4 to 3.4 kV for film thicknesses between 5 and 60 μm . The mixed electrolyte of 8 vol.% sulfuric acid and 3 wt.% oxalic acid exhibited significantly high dielectric breakdown voltage of 3.4 to 3.9 kV for the 50 μm thick film on AA6061, compared to that formed in single electrolytes of sulfuric acid, oxalic acid, or phytic acid. The AAO films formed on AA6061 and AA5052 alloys using two-step anodizing process (first step anodizing in sulfuric acid solution and second step anodizing in oxalic acid solution) showed higher dielectric breakdown voltages of 2.2

to 3.3 kV than the values obtained from one-step sulfuric acid anodizing (1.7 to 2.5 kV) for a film thickness of 50 μm .

Pham et al. [18] studied the dielectric breakdown behavior of the AAO films formed on pure aluminum in sulfuric acid (SA) and oxalic acid (OA) solutions. The study revealed that the dielectric breakdown voltage of the AAO films increased with the increasing concentration of both SA and OA solutions up to 15 vol.% and 6 wt.%, respectively, above which it decreased slightly. The dielectric breakdown voltage of the AAO films increased linearly with film thickness and its slope was reduced more rapidly in SA than OA as the film thickness increased. The greater reduction for SA films was attributed to higher porosity and the electrical nature of incorporated anions [18]. They [18] also found that the dielectric breakdown voltage of the AAO films formed in OA solution is approximately 25% higher than that in SA solution, which is likely due to the lower porosity of the films formed in OA solution.

After the dielectric breakdown tests, circular holes and cracks were observed on the AAO films. These defects originated from the spots where the testing tip contacted the AAO film surface. The crack length increased with film thickness for SA films thicker than 30 μm , while it remained nearly constant for OA films. The shorter cracks in the OA films was attributed to the generation of relatively lower tensile stress at the oxide/metal interface during the dielectric breakdown event, due to the lower porosity of the films compared to the SA films. Pham et al. [18] concluded that the dielectric breakdown resistance of the AAO films formed on pure aluminum is influenced not only by film thickness but also by anion type and concentration of anodizing solution.

Jeong et al. [35] studied the corrosion resistance, dielectric breakdown voltage, and hardness of the AAO films formed on

two different aluminum alloys of AA5052 and AA6061. They reported that optimal applied current density was 25 $\text{mA}\cdot\text{cm}^{-2}$ for the best combination of corrosion resistance, hardness, and dielectric breakdown voltage of the AAO film [35]. They revealed that the dielectric breakdown voltage of the AAO film is improved by boiling water sealing and further improved by using additives in the boiling water sealing solution.

Jeong et al. [37] also investigated the properties of double-layered anodic oxide films on AA5052 and AA6061 alloys using a two-step anodizing process in sulfuric acid and oxalic acid electrolytes. Their results showed that the double-layered films exhibited higher dielectric breakdown voltages compared to the single-layered films formed in sulfuric acid solution, with the values increasing as the thickness ratio of the inner layer to the outer layer increased. However, the double-layered films still had lower dielectric breakdown voltages than the single-layered films formed in oxalic acid for both alloys.

Park et al. [38] studied the dielectric breakdown voltage of the AAO films formed on AA6061 alloy in 20 vol.% sulfuric acid solution and a mixed solution of 8 vol.% sulfuric acid and 3 wt.% oxalic acid. They found that the AAO film formed in the mixed electrolyte exhibited 33% to 40% higher dielectric breakdown voltage (3.4 to 3.9 kV) compared to the film formed in the 20 vol.% sulfuric acid solution (2.5 to 2.9 kV) for a film thickness of about 50 μm . The number of pores in the AAO film formed in the mixed electrolyte (1014 EA/ μm^2) was found to be much higher than that in the 20% sulfuric acid solution (676 EA/ μm^2), and the pore size was also larger in the mixed solution. Despite higher porosity, the mixed solution films showed better dielectric breakdown resistance of the AAO film. This was ascribed to the influence of organic anions incorporated

into the AAO film. Park et al. [38] also investigated the effect of decreasing current density during anodizing ($10 \text{ mA}\cdot\text{cm}^{-2} \rightarrow 7.8 \text{ mA}\cdot\text{cm}^{-2} \rightarrow 5.5 \text{ mA}\cdot\text{cm}^{-2}$). The dielectric breakdown voltage was increased by using decreasing current density during anodizing which was attributed to the modification of the internal pore structure of the AAO film.

6. Conclusions

In this paper, we reviewed the dielectric breakdown behavior and breakdown voltages of the AAO films in air environment. The dielectric breakdown mechanisms, types of dielectric materials, and fabrication methods for dielectric aluminum oxide layers were presented. Then, finally, current studies on the dielectric breakdown properties of the AAO films formed on different aluminum alloys in various electrolytes were summarized. Various dielectric breakdown mechanisms of dielectric materials, including electron avalanche breakdown, thermal breakdown, electromechanical breakdown and others, were described in detail. Among various dielectric materials, aluminum oxide has been frequently employed because of its relatively high dielectric strength, good thermal conductivity, excellent mechanical strength and low cost. When comparing fabrication methods for dielectric aluminum oxide layer, anodizing is a preferred choice because it offers precise film thickness control, excellent adhesion to the substrate, high film thickness and cost-effectiveness. Recent studies on the dielectric breakdown of the AAO films have revealed several key findings. The alloying elements and electrolyte composition for anodizing play important roles in dielectric breakdown of the AAO films. The films formed on AA5052 and AA6061 alloys exhibit higher dielectric breakdown resistance than those formed on pure aluminum, and oxalic acid electrolyte

produces the AAO films with more improved dielectric breakdown resistance than sulfuric acid electrolyte. The dielectric breakdown resistance of the AAO films was reported to be improved by two-step anodizing process in mixed electrolytes and sealing treatments with additives.

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