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APPLIED RESEARCH

DC Flashover in Printed Circuit Boards at Low Gas Pressures: Mechanism and Mitigation Recommendations

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ABSTRACT PCB layouts with different polygon shapes and insulation distances were prepared and their surface flashover voltage subjected to different ramping rates were measured at different temperatures and different low gas pressures for emulated high-altitude conditions. The dependence of the surface flashover voltage on effects of gas pressure, surface insulation distance, temperature, and polygon shape was studied. Modulation efforts which include tailoring the local surface conductivity and local topography modification were performed to increase the flashover of PCB, and the related mechanism was studied. The results showed that the voltage ramping rate plays an important role in determining flashover voltage. The flashover voltage is lower when the sample is subjected to a rapid voltage ramping rate than with a slow ramping rate. This phenomenon is more prominent towards ambient pressure. The increase in temperature results in a decrease in flashover voltage at 100 kPa, while at 20 kPa and 10 kPa, the influence of temperature on flashover becomes less significant. Through-holes designed in the PCB have a positive role in increasing flashover voltage at lower pressures. However, at 100 kPa, the holes no longer contribute to any higher flashover voltage. Modification of local surface conductivity has no contribution in increasing the flashover voltage, while a surface coating with a surface conductivity of 10^{-10} S dramatically decreases the flashover voltage. The work presented in this paper provides a reference for the design and modification of PCB layouts for use in future aerospace hybrid propulsion systems.

INDEX TERMS PCB, flashover, more-electric aircraft, partial discharge, surface charge.

I. INTRODUCTION

Compared with traditional airplanes, the use of power electronic equipment in future hybrid compulsion is projected to increase dramatically. The voltage of the power supply in most commercial electric aircraft has been limited to 270 V DC, but is on the rise [1], [2]. In order to meet its increasing requirements in passenger capacity and military use, the power supply of more-electric aircraft needs to be improved urgently. To reach this goal, the voltage of

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the power supply system of the more-electric aircraft may reach several thousand volts. Research institutes and companies including Airbus, NASA, and Collins Aerospace have developed strategic research plans on the improvement of the voltage level and stability of the hybrid power system of more-electric aircraft. However, with the voltage level of the power supply increased, the insulation of the propulsion system would face new challenges, and the insulation problem at low air pressure at high altitudes would become more prominent.

As one of the core components of the hybrid propulsion system, the printed circuit board (PCB) plays a significant role in the safety and reliable operation of the more-electric aircraft. However, in existing DC power electronic components, due to charge injection, surface charge accumulation, dipole rotation, and partial discharge, etc., local electric field near the components could be enhanced which potentially results in flashover of PCB [3]. Additionally, the pressure-drop at high altitude leads to a largely reduced gas ionization inception voltage, and hence a much lower flashover voltage [4], [5].

The occurrence of surface discharge is affected by parameters such as voltage frequency, gas pressure, temperature and humidity [6]. The right part of Paschen's curve indicates that the dielectric strength of air at a uniform electric field decreases as the gas pressure decreases. Commercial and military aircraft usually fly at an altitude of 6 ∼ 15 km, corresponding to pressure variations ranging from 100 kPa to 10 kPa. The low-pressure environment exacerbates the risk of discharge on critical components in the PCB and brings potential danger to the more-electric aircraft.

The flashover properties at low gas pressures have been studied by previous researchers. Zhang et al. found that the flashover voltage decreases with the decrease of gas pressure, which is largely determined by the insulator string at AC voltage [7], [8]. The altitude effects on AC flashover of insulators were investigated based on simulation, and the results showed that the critical AC withstand voltages of polluted simple-shaped insulators vary approximately with the square root of ambient pressure [9]. Regarding the flashover of PCBs, Grosjean et al. studied the gas breakdown characteristics of wire-plane and PCB configuration as a function of pressure and electrode spacing [10]. Based on the comparison between the test results and the existing research, the conclusions and recommendations of the published research were discussed and refined [10].

All these previous studies suggest that flashover of PCB at DC voltage has still not been well investigated, and the effects including voltage ramping rate, gas pressures, temperatures, and insulation distances on flashover properties are not fully understood. Very few researches focus on the flashover mitigation methods. The content in this paper focuses on the flashover phenomenon and the influencing factors that the PCB in the more-electric aircraft may encounter to shed lights on the design and modification of PCB layouts for use in future aerospace hybrid propulsion systems.

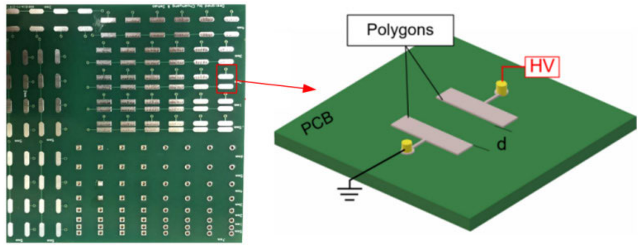


FIGURE 1. PCB used for the tests and the schematic diagram of an enlarged experimental sample.

TABLE 1. The polygon shape and the insulation distance.

Polygon shape/ Abbreviation	Schematic diagram of polygon electrodes	Insulation distance between two polygons, **d** (mm)			
Rectangle with round sides/R	6mm, 2mm	0.5	1	2	3
Rectangle with right angles/S	6mm, 2mm	0.5	1	2	3

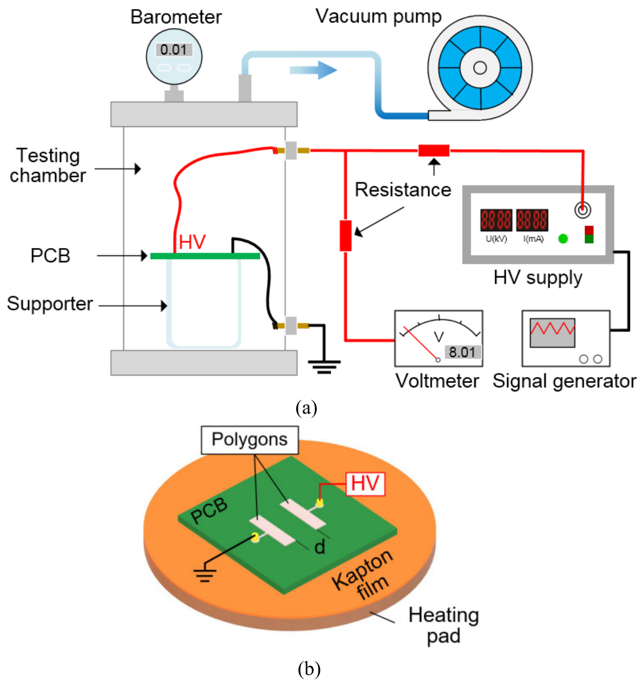
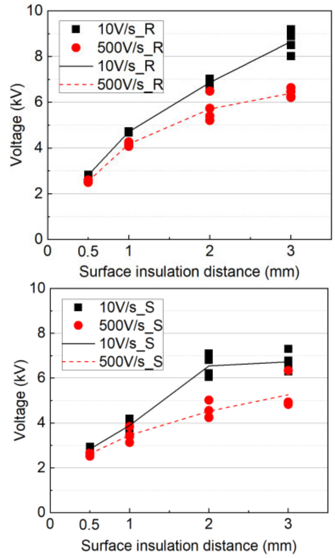


FIGURE 2. Schematic diagram of experimental setup. (a) the flashover test setup, and (b) the sample with a heating pad.

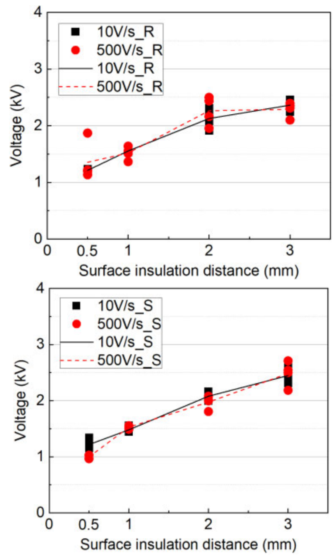
II. EXPERIMENT DESCRIPTION

A. SAMPLE PREPARATION

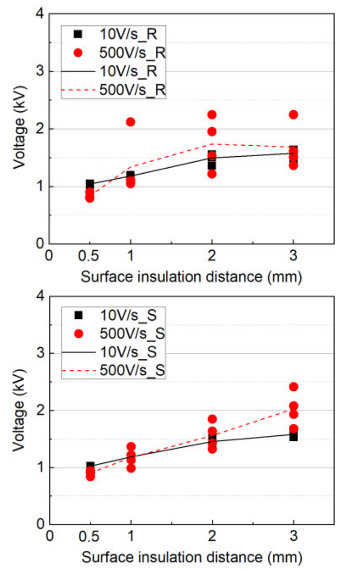
The experimental sample is FR-4 e-glass reinforced epoxy resin laminated single-layer PCB with a dimension of 10 cm × 10 cm × 0.3 cm. The polygons, which is made of copper covered with a tin coating, are designed into different shapes and insulation distances on the PCB as electrodes. The electrode is led out by the aluminum-clad conductor to a via near the polygon, which is used to connect the high voltage and ground, as shown in Figure 1. The polygon shape and the insulation distance are shown in Table 1.



(a) Flashover voltage of polygons at 100 kPa



(b) Flashover voltage of polygons at 20 kPa



(c) Flashover voltage of polygons at 10 kPa

FIGURE 3. The flashover voltage of polygons with round sides and right angles measured at different voltage ramping rate and different gas pressures. The curve represents the average flashover voltages and the points are the measured flashover voltage data points.

B. FLASHOVER TEST SETUP

Figure 2 (a) shows the schematic diagram of the surface flashover test setup. The PCB was placed on the top of a glass supporter which is fixed in a gas chamber. The vias corresponding to the polygonal electrodes were connected to the high voltage and ground through wires, respectively. A vacuum pump was used to control the gas pressure inside the chamber. The ramp voltage was controlled by a signal generator, whose output was amplified by a high voltage supplier and then applied to the sample. The terminal voltage was measured by a voltmeter through a divider to record the flashover voltage.

During the test, the gas pressure inside the chamber was set at 100 kPa, 20 kPa, and 10 kPa, corresponding to the pressures at which the aircraft cruises at different altitudes, namely 0 m, 11000 m, and 16000 m, respectively. After the pressure stabilized, the voltage was applied. The ramping rates of 10 kV/s and 500 kV/s were used, and the recovery time between two flashovers was 1 min. Two samples were tested for each experiment and each sample was measured two times. The temperature and relative humidity during the test were 17 °C and ∼40 %. A heating element was attached to the back of the PCB in the flashover test at higher temperature, as shown in Figure 2 (b). The flashover voltage was measured after the temperature was stable for 30 min.

III. FLASHOVER PROPERTIES SUBJECTED TO DIFFERENT INFLUENCING FACTORS

In this chapter, the results regarding the effects of polygon shape, insulation distances, voltage ramping rates, and temperatures on flashover voltage were presented.

A. POLYGON SHAPE, INSULATION DISTANCE, AND VOLTAGE RAMPING RATE

Figure 3 shows the flashover voltages of the polygons with round sides and right angles measured at different voltage ramping rates and different gas pressures. The flashover voltage gradually increases with the increase of the insulation distance, and there is a trend of saturation. This feature is the most obvious at 100 kPa.

At a higher voltage ramping rate, the flashover voltage appears lower, and this trend gradually increases as the insulation distance increases. However, this trend becomes less obvious at lower gas pressures. Taking Sample_R at 100 kPa as an example, with insulation distance increased from 0.5 mm to 3 mm, the flashover voltage measured at a lower ramping rate of 10 V/s is increased only by 1.03 times compared to a higher increase of 1.32 times at a higher ramping rate of 500 V/s. However, at low pressures of 10 and 20 kPa, the effect of voltage ramping rate on the increment of flashover voltages over the insulation distance appears diminishing.

The influence of pressure on flashover voltage is apparently predominant. When the pressure drops, the dispersion of the flashover voltages increases sharply, especially for Sample_S at 10 kPa. In addition, similar to the results in previous studies, the flashover voltage decreases as the pressure drops. For both polygonal samples, the flashover voltage over a 0.5 mm insulation distance at 100 kPa is approximately 1.8 times and 2.8 times the flashover voltage at 20 kPa and 10 kPa, respectively. For a longer insulation distance of 3 mm, the flashover voltage varies greatly depending on the shape of the sample, and the voltage ramping rate also has a significant effect on the flashover voltage. For Sample_R, when 10 kV/s is used, the flashover voltage at 100 kPa is 3.6 times and 5.6 times higher than that of 20 kPa and 10 kPa, respectively. When at 500 kV/s, the corresponding flashover voltage is 2.8 times and 4.2 times higher than that of 20 kPa and 10 kPa, respectively. However, for Sample_S, when 10kV/s is used, the flashover voltage of Sample_S at 100 kPa is 2.6 times and 4.4 times higher than that of 20 kPa and 10 kPa, respectively, whereas under 500kV/s, the corresponding voltage is 2 times and 2.5 times compared with that measured at 20 kPa and 10 kPa, respectively.

B. TEMPERATURE

Figure 4 shows the flashover voltage of samples with an insulation distance of 1 mm at different voltage ramping rates at 20 °C and 80 °C. At 100 kPa, an increase in temperature corresponds to a lower flashover voltage. For example, at 10 kV/s, the flashover voltage at 20 °C is 4.7 kV, but at 80 °C the flashover voltage drops to near 4.3 kV. In addition, the flashover voltage dropping rate at 500 V/s is relatively lower than that at 10 V/s. The flashover voltage of 500 V/s at 20 °C and 80 °C is 82 % and 92 % of the flashover voltage at 10 V/s.

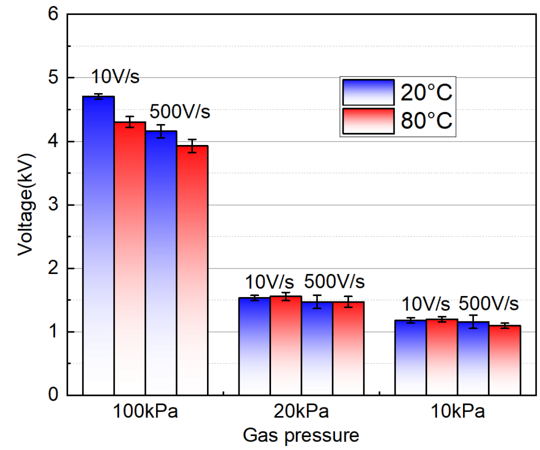
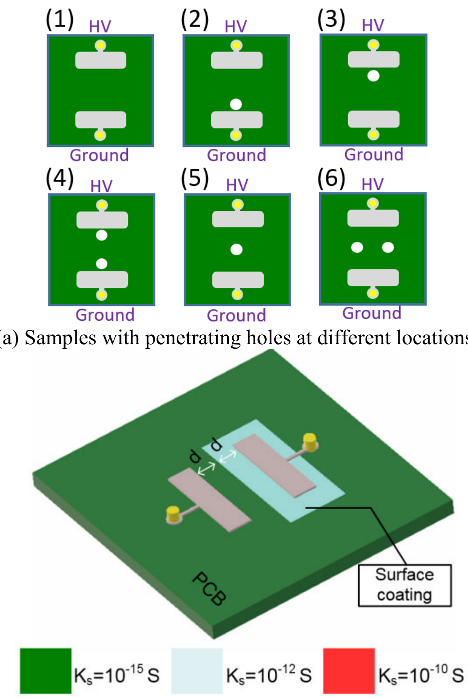


FIGURE 4. Flashover voltage of round sides polygons with insulation distance of 1 mm at different voltage ramping rate at 20 °C and 80 °C.



(a) Samples with penetrating holes at different locations.

(b) Samples with modified surface conductivity.

FIGURE 5. Schematic diagram of samples with different modification methods. (a) Samples with holes at different positions between electrodes, and (b) samples with surface conductivity modified at different positions.

However, at 20 kPa and 10 kPa, the change in temperature has a very little effect on the flashover voltage.

IV. MODIFICATIONS TO BOOST FLASHOVER VOLTAGE

In this chapter, PCB samples with penetrating holes in the insulation region and the PCB samples with tailored surface conductivity near electrodes were prepared. The flashover voltage was measured.

A. SAMPLE PREPARATION

The shape of the electrode of samples prepared for the local topography modification was a rectangle with round sides

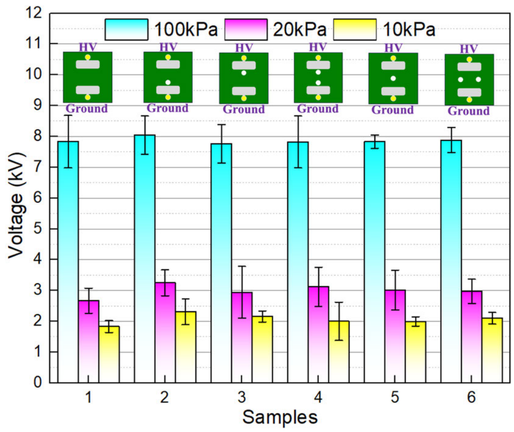


FIGURE 6. Flashover voltage of local topographically modified samples at different gas pressures.

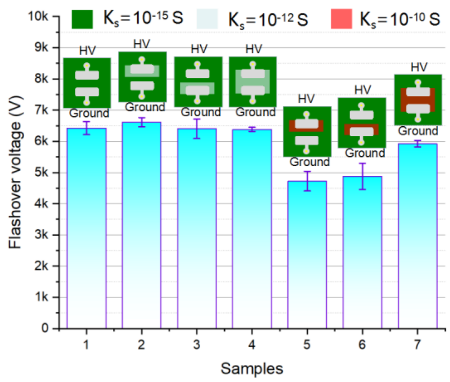


FIGURE 7. Flashover voltage of samples with modified surface conductivities at 100 kPa.

with an insulation distance of 4 mm. Holes with a diameter of 1 mm were created at different locations in the insulation area. The locations of these holes were arranged close to the HV electrode, close to the ground electrode, and in the central part of the insulation area, respectively. Six types of configurations were prepared with schematic diagrams shown in Figure 5(a). The voltage ramping rate during the test was 500 V/s.

The shape of the electrode of samples prepared for the surface conductivity modification was rectangular with round sides, and the insulation distance between the electrodes is 3 mm. The surface conductivity of the insulation region near one of the electrodes was modulated into two surface conductivities including 1×10^{-12} S and 1×10^{-10}S by a manner of magnetron sputtering of Au/Pd with different modulation time and output power. During the treatment, a PET film with a thickness of 200 μm was used as the shadow mask for the sputtering process. The coated area and the insulation area without coating were of the same width d, as is shown in Figure 5 (b).

B. TEST RESULTS FOR SAMPLES WITH LOCAL TOPOGRAPHY MODIFICATION

Figure 6 shows the flashover voltage of local topographically modified samples at different gas pressures. At 100 kPa, the flashover voltage is between 7.5 kV to 8.5 kV for all samples, and the change of flashover voltage due to the local topography modification is not obvious. However, at lower pressures, the hole is effective in increasing flashover voltage, showing an increased flashover voltage, especially at 10 kPa for all samples. Additionally, samples with one hole near the ground (sample_2) present the best property in increasing the flashover voltage. For example, the flashover voltage of sample_2 reaches 3.2 kV and 2.3 kV at 20 kPa and 10 kPa, corresponding to 23 % and 28 % enhancement over the untreated samples. While for other local topography-modified scenarios, the increasing rate in flashover voltage remains at less than 15 % and 17% at 20 kPa and 10 kPa, respectively.

C. TEST RESULTS FOR SAMPLES WITH TAILORED SURFACE CONDUCTIVITY

Figure 7 shows the flashover voltage of samples with modified surface conductivities at 100 kPa. Modifying local surface conductivity in this paper does not show a positive result in increasing the flashover voltage. For samples modified with a conductivity of 10^{-12} S (sample_1, sample_2 and sample_3), the flashover voltage remains at approximately 6.5 kV, which is the same as that of the untreated sample (sample_1).

On the contrary, a higher surface conductivity (10^{-10} S) results in significant decrease in flashover voltage for all scenarios mentioned in this paper. For example, for samples with modified surface conductivity near the HV electrode and the ground electrode (sample_5 and sample_6), the flashover voltage drops 26 % and 27 % compared with that of the untreated sample, and for sample with modified surface conductivity on the whole surface (sample_7), the flashover voltage slightly increases compared with sample_5 and sample_6 but still lower than that of the untreated samples (sample_1).

V. DISCUSSION

A. ROLE OF PRESSURE, RAMPING RATE, AND TEMPERATURE IN TRIGGERING FLASHOVER

The effect of gas pressures on gas breakdown has been extensively discussed by previous researchers. According to Paschen's law, the breakdown voltage between two electrodes in a gas can be roughly calculated as a function of the gas pressure and the gap distance. This can be explained by the probability of the potentially triggered ionization during ion acceleration at different pressures and gas gaps.

However, it should be emphasized that the variations in flashover voltage at different gas pressures in this paper is not only influenced by the electron collision, which is a function of the gas pressure, but also a result of the polarization of the insulation, especially at higher gas pressures. In other words, the gas pressure and the polarization of the solid insulation together contribute to determining the flashover voltage. The most intuitive example is that the flashover voltage differs

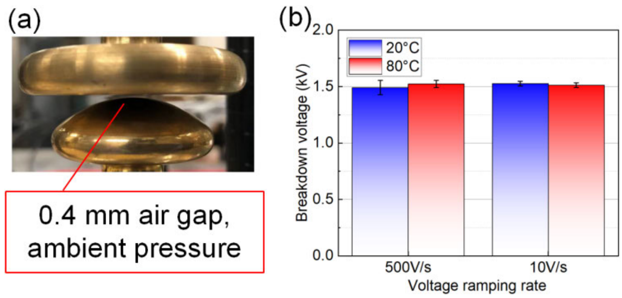


FIGURE 8. (a) Schematic diagram of a 0.4 mm gas gap between a ball-plate electrode arrangement, and (b) gas breakdown voltage at different temperatures and with different voltage ramping rate.

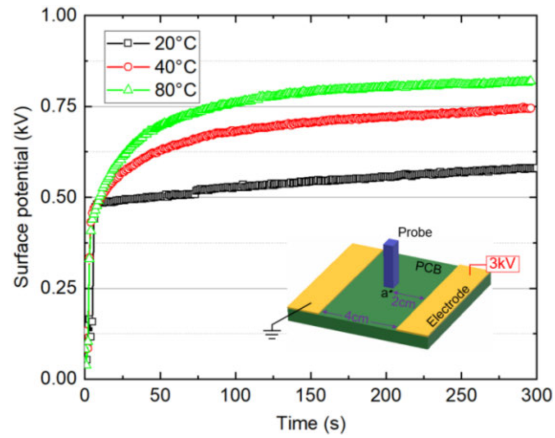


FIGURE 9. Online measurement results of surface potential on a PCB at 3 kV at different temperatures.

at different ramping rates, i.e. the flashover voltage is lower when a higher voltage ramping rate is applied, and this phenomenon is more obvious at higher pressure, as verified by the findings in Figure 3.

When an electric field is applied to an insulation material, a dipole moment is formed and the polarization occurs instantly. The polarization, including electronic polarization, ionic polarization, dipolar polarization, and space charge polarization, affects the surface electric field distribution near the triple junction and further influences the flashover voltage. To be more specific, if a rapid ramping rate of voltage was applied on an insulation, the electronic polarization and ionic polarization instantly build up at the position where there is very dense electric field, i.e. the triple junction. In this case, the surface electric field due to the polarization is modified and the surface partial discharge (PD) is mitigated [11]. While for an insulation applied with a slow ramping voltage, apart from the electronic polarization and ionic polarization, dipolar polarization and space charge polarization would occur during the process of ramping and modify the electric field near the triple junction. In addition, our recently published paper also verifies that the surface charge migration in the vicinity of the triple junction can be a way to effectively suppress the surface PD activity [11]. Since the build-up of the electric field to mitigate surface electric field near the triple junction due to dipolar polarization and space charge polarization needs more time, the effect of these two types of polarization on increasing the flashover voltage at lower pressures is not that significant as that at high pressures, due to a much shorter ramping time and lower applied electric field before flashover occurs.

At high temperatures, the flashover voltage is determined by two factors: the thermionic emission and the thermally stimulated polarization. For temperature-stable gases such as nitrogen, the departures of gas molecular can only be found at temperatures of higher than 1000 °C and the thermionic emission thereby results in a lower breakdown voltage [12]. Therefore, the thermionic emission of the gas molecule is usually not considered in the case of flashover of dielectric polymers due to the reason that the operating temperature of these dielectric polymers cannot reach that high. As it can be seen in Figure 8, the breakdown voltage of a 0.4 mm gas gap at 20 °C is very similar compared with that measured at 80 °C. Additionally, the ramping rate has no influence on the breakdown voltage. This is due to the reason that there is no solid dielectric involved in this arrangement. For dielectric polymers, the effect of temperature or temperature gradient on flashover lies in the effect of temperature on insulation polarization. At high temperatures, more charges would be injected to the bulk of the insulation and these charges migrate along the electric field lines, affecting the surface electric field. Figure 9 shows the online measurement results of surface potential on a PCB at 3 kV at different temperatures. It can be found that the sharp increase of surface potential at the first few seconds was mostly contributed by the electronic polarization and ionic polarization which occur instantly after the voltage was applied. With the increase of time, the surface potential at a point *a* becomes significantly higher at higher temperatures compared with that at lower temperatures, which means that the injected charges migrate from the high voltage electrode to the grounded electrode. In other words, the space charge polarization becomes dominant in this process. If the DC voltage was held for a long time, the charge migration would create an ‘‘analogous ineffective region’’ near the HV electrode, and the expansion of the ‘‘analogous ineffective region’’ results in a decrease in flashover voltage [13]. It should be noted that the above discussion is based on DC voltage, and the triggering of flashover at AC voltage is completely different.

B. DISCUSSION AND RECOMMENDATIONS ON DISCHARGE MITIGATION SOLUTIONS

Material modification methods can be used to regulate surface charge behaviors and modify surface electric field, through which the flashover voltage can be boosted. Our previous published paper illustrates methods to regulate surface charge behaviors, which includes physical etchings, chemical modifications, and surface coatings [14]. It should be noted that before implementing any modification methods, at DC voltage, we need to confirm firstly the weak point of the electrode-insulation arrangement. After that, we can start to consider how we want to regulate the charges and boost the flashover voltage [15]. One example could be, if the modification methods were performed out of the purpose of suppressing surface partial discharges, a slight increase in surface conductivity might be helpful since an increased surface conductivity is helpful for surface charge migration in the vicinity of the triple junction and the electric field near the triple junction could be modified [11]. However, an increased surface conductivity results in an increase of the tangential electric field component and may result in an expansion of ''analogous ineffective region'', which might not be helpful in promoting the flashover voltage.

Figure 6 presents that locally distributed holes on PCB can be helpful in increasing flashover voltage at low gas pressures, while this method is not that effective at ambient pressure. In a gas-solid interface scenario, before flashover occurs, the following physical processes exist in the insulation gap: collision ionization of gas molecules, formation of streamers, and establishment of flashover channels. When the pressure decreases from 100 kPa to 10 kPa, the density of gas molecules decreases, which leads to a decrease in the collision probability of electrons moving toward the anode driven by the electric field force. Since the collision between electrons and gas molecules loses energy, the kinetic energy of electrons is more likely to increase under low pressure, which promotes the collision ionization, and thereby increasing the probability of electron avalanches and flashovers. Penetrating holes on the insulating surface is helpful in scattering or blocking the electron trajectory, thus prevents the electrons from accumulating energy and inhibits the formation of electron avalanches. Since the number of electrons and molecules at low pressures is lower than that at high pressures, the holes on the surface at low pressures is thereby more conducive in suppressing surface discharge and increasing the flashover voltage. The results in Figure 6 are also corroborated. Similar theories are also mentioned in reference [16] in the case of high vacuum.

An increase in surface conductivity modifies the electric field near the triple junction and is helpful in PD mitigation. However, an increased surface conductivity enhances the tangential electric field component, making it more prone to flashover. This explains why the flashover voltage of modified sample with a surface conductivity of 10^{-12} S is not helpful in increasing flashover voltage, while for samples 5-7 which have a surface conductivity of 10^{-10} S, the flashover voltage drops dramatically.

VI. CONCLUSION

In this paper, the flashover was tested using polygon electrodes with different shapes and insulation distances on the PCB at different gas pressures, temperatures, and voltage ramping rates. Modification methods including penetrating holes and surface conductivity modulations on the PCB were implemented. The main conclusion is as follows.

(1) The voltage ramping rate plays an important role in determining flashover voltage, which is due to the polarization processes of the solid insulation. The flashover voltage is lower at rapid ramping rate compared with that at slow ramping rate, and this phenomenon is more prominent at higher gas pressures. These imply the roles of dipolar polarization and space charge polarization and their possible contribution to the increasing of flashover voltage at slow ramping rate.

(2) The increase in temperature results in a decrease of flashover voltage at 100 kPa, while at 20 kPa and 10 kPa, the influence of temperature on flashover becomes less.

(3) Penetrating holes designed in the PCB between electrodes have positive role in increasing flashover voltage at lower gas pressures. However, at 100 kPa, the holes do not contribute any longer.

(4) Lowering the local surface resistivity of the insulation near electrodes does not appear effective in increasing flashover voltage, and the surface conductivity of 10^{-10} S on the contrary decreases the flashover voltage.

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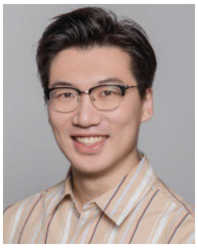

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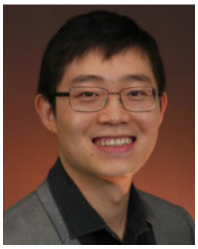

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