Optimum Breakdown Charge for Maximum Dielectric Strength in Spark Conditioning in Vacuum under a Non-uniform Electric Field

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ABSTRACT

Spark conditioning is an effective method of increasing the dielectric strength in vacuum. In this paper, we determined the breakdown (BD) charge dependence for spark conditioning in vacuum under various non-uniform electric fields and with different anode materials. We discuss the BD mechanism in terms of BD arising from anode heating or cathode heating. Experimental results revealed that for anode heating BD, the longer the gap distance, the larger the BD charge needed to obtain maximum dielectric strength. In contrast, for cathode heating BD, the BD charge for maximum dielectric strength was smaller than that for anode heating BD. From these results, we estimated the optimal BD charge to maximize the 50% BD electric field strength, i.e. the dielectric strength, for spark conditioning in vacuum.

Index Terms — **Vacuum discharge, conditioning, non-uniform electric field, vacuum circuit breakers, breakdown.**

1 INTRODUCTION

VACUUM interrupters (VIs) and vacuum circuit breakers (VCBs) are expected to be used for high-voltage applications because of their high insulation performance, good current interruption performance, and environmental friendliness [1-4]. Spark conditioning is used to improve the dielectric strength in vacuum [5]. The conditioning effect has a maximum value with respect to discharge current, and the breakdown (BD) charge at which the maximum conditioning effect is obtained depends on the cathode material [6].

We have previously investigated the effects of the BD charge on spark conditioning under a non-uniform electric field, based on the mechanism of BD initiation [6]. It is expected that the larger BD charge leads to getting the higher conditioning effect, but the excess BD charge causes the damaging effect of the electrode. Therefore, the maximum dielectric strength by spark conditioning is achieved by the balance between the conditioning and the damaging effects on the electrode surface, and these effects depend on the BD mechanism. Although various theories of BD in vacuum have been proposed [7, 8], assuming that clumps on the electrodes are sufficiently removed in the final stage of spark conditioning, cathode heating BD (CH-BD) or anode heating BD (AH-BD) will mainly occur. By applying a high voltage to the electrode system during spark conditioning, electron emission from the cathode heats the electrode and vaporizes the electrode material. In CH-BD, cathode heating leads to BD [7]; in contrast, in AH-BD, anode heating leads to BD [8]. The possible BD mechanism is dominated by the conditions and configuration of the electrode system, and the difference in the BD mechanism mediates the effect of the conditioning on the magnitude of BD charge. Therefore, to increase the dielectric strength in vacuum, we must clarify the optimum BD charge for spark conditioning with various gap lengths and electrode materials, based on the BD mechanism.

In this paper, we focus on the BD charge dependence for spark conditioning in vacuum for various non-uniform electric fields, gap lengths, and anode materials. Then, we discuss the optimal BD charge for the spark conditioning in vacuum.

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2 EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows the experimental setup. We repeatedly applied a negative lightning impulse voltage generated by an impulse generator (I.G.) to the rod-plane electrode system in a vacuum chamber. We used the up-down method for the repetitive impulse voltage application. In the up-down method, the initial charged voltage of the I.G. was 30 kV, and the charged voltage ΔV was increased in 10 kV increments. The applied voltage and the discharge current were observed with a voltage divider and a current transformer (CT), respectively, and were recorded with a digital oscilloscope. The vacuum pressure in the chamber was kept around 10^{-6} Pa.

Figure 2 shows the configuration of the rod-plane electrode system. The gap distance d was from 1 to 30 mm and the tip radius r of the rod electrode was 1, 2, or 5 mm. The rod electrode (cathode) was made with oxygen-free high thermal conductivity copper (Cu), and the grounded plane electrode (anode) was made with Cu or stainless steel (SS). We changed the discharge current at BD by varying the limiting resistance R_L to 30 Ω, 60 Ω, 2 kΩ, 11 kΩ, and 20 kΩ. Figure 3 is typical waveforms of applied voltage and discharge current when BD occurred during the conditioning process. The discharge current was suppressed by higher R_L. Most of BDs during conditioning process occurred at the peak of applied voltage.

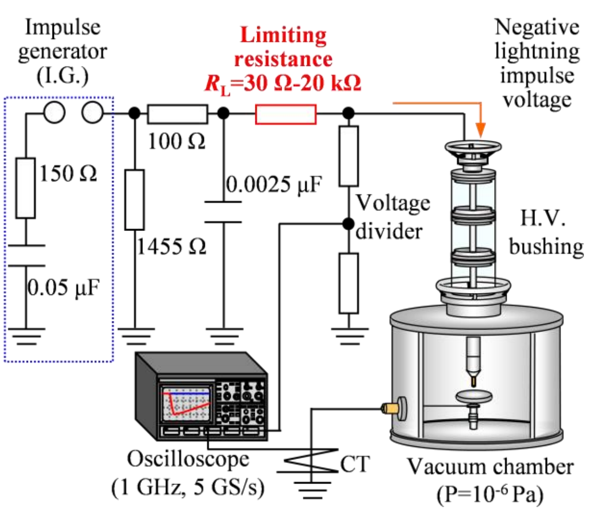
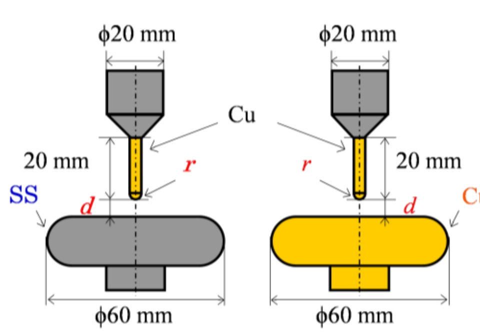
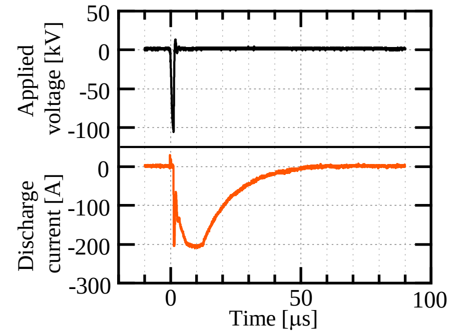


Figure 1. Schematic of the experimental setup.

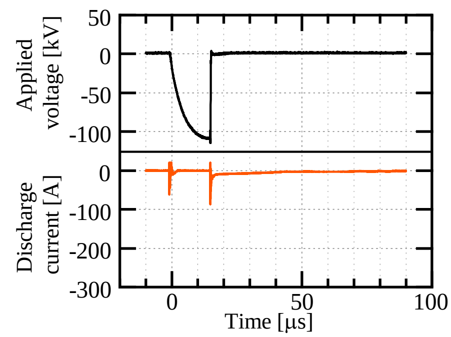


(a) Anode : SS (b) Anode : Cu

Figure 2. Schematic of the electrode configuration.



(a) R_L = 60 Ω, applied impulse voltage: 1.2/50 μs.



(b) R_L = 11 kΩ, applied impulse voltage: 15/60 μs.

Figure 3. Typical waveforms of applied voltage and discharge current when BD occurred during conditioning process. Anode: SS, d = 5 mm. The charged voltage of I.G. was 130 kV.

3 RESULTS AND DISCUSSION

3.1 CONDITIONING HISTORY

Figure 4 shows the conditioning history for gap distances of d = 2, 5, and 20 mm. In all cases, r = 2 mm and R_L = 60 Ω. The 50% BD voltage (V_{sat}) after conditioning saturation is shown by horizontal lines. When the maximum BD voltage did not change over 300 voltage applications, we considered the conditioning saturated. This saturation was also confirmed by stabilization of Weibull plot of BD voltage [9]. For d = 2 mm (Figure 4a), V_{sat} was similar regardless of the anode material. However, for d = 5 and 20 mm (Figures 4b and 4c), BD voltage decreased during the conditioning process for the SS anode. This implies that the electrodes were damaged during the conditioning. V_{sat} was lower for the SS anode than for the Cu anode.

Figure 5 shows the development of the BD spot on the rod cathode surface for the Cu cathode and SS anode, observed by the digital camera at d = 5 mm (conditions shown in Figure 4b). On the Cu anode (Figure 5a), the BD spot started at the tip of the electrode and moved to the wider region of the electrode with a lower field as the number of voltage applications increased, which is consistent with [10], i.e. the development of conditioning was dominated by the conditioning degree at the tip of electrode. For the SS anode, the BD spot tended to be concentrated at the tip of the cathode, which implies that the cathode tip was heavily damaged.

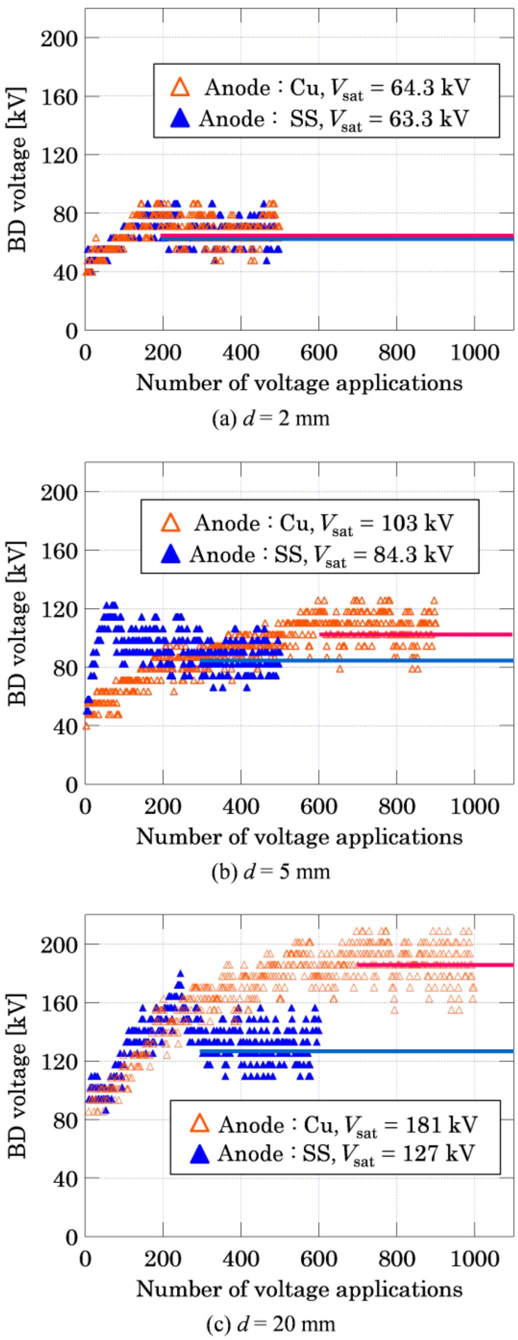


Figure 4. Conditioning history (r = 2 mm, R_L = 60 Ω).

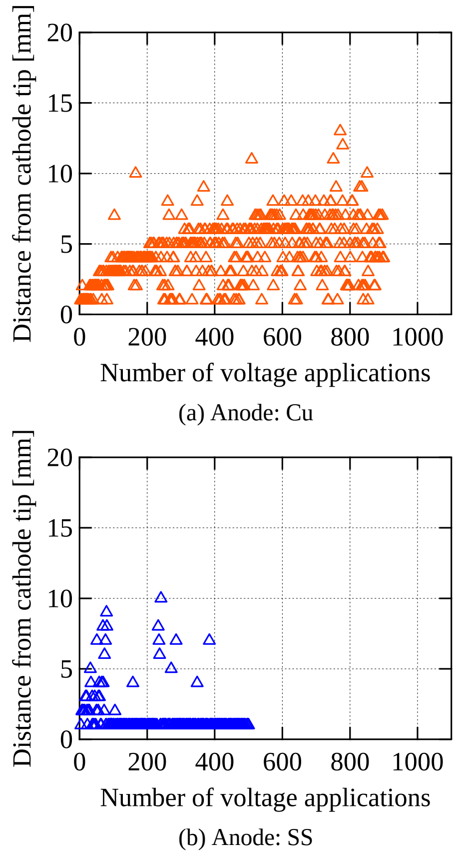


Figure 5. Development of the BD spot on the cathode surface (r = 2 mm, R_L = 60 Ω, d = 5 mm). The resolution of the BD spot is 1 mm. On the vertical axis, 0 mm is the cathode tip, and 20 mm is the cathode base (see Figure 2).

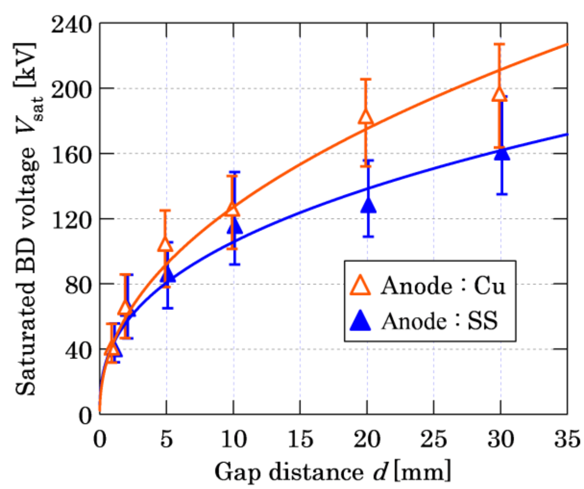


Figure 6. Relationship between V_{sat} and d (r = 2 mm, R_L = 60 Ω).

3.2 GAP DISTANCE DEPENDENCE OF CONDITIONING CHARACTERISTICS

Figure 6 shows the relation between V_{sat} and d. In this figure, the error bars indicate the maximum and minimum values of BD voltage after the conditioning saturation. For short gap distances ($d \leq 2$ mm), V_{sat} was similar for both anode materials, whereas for long gap distances (d = 5–30 mm), V_{sat} for the Cu anode was higher than that for the SS anode.

Figure 7 shows microscope images of the surface at the tip of the Cu cathode before and after conditioning. Before conditioning, machining traces were observable as several straight trails. After conditioning, for short gap distances, severe melting was visible and the machining traces had disappeared, regardless of the anode material. In contrast, for long gap distances, the cathode for the Cu anode melted less than the cathode for the SS anode.

For short gap distances, CH-BD tends to occur because a high electric field appears at a low voltage. CH-BD does not depend on the anode, so it is considered that similar conditioning characteristics were obtained for different anode

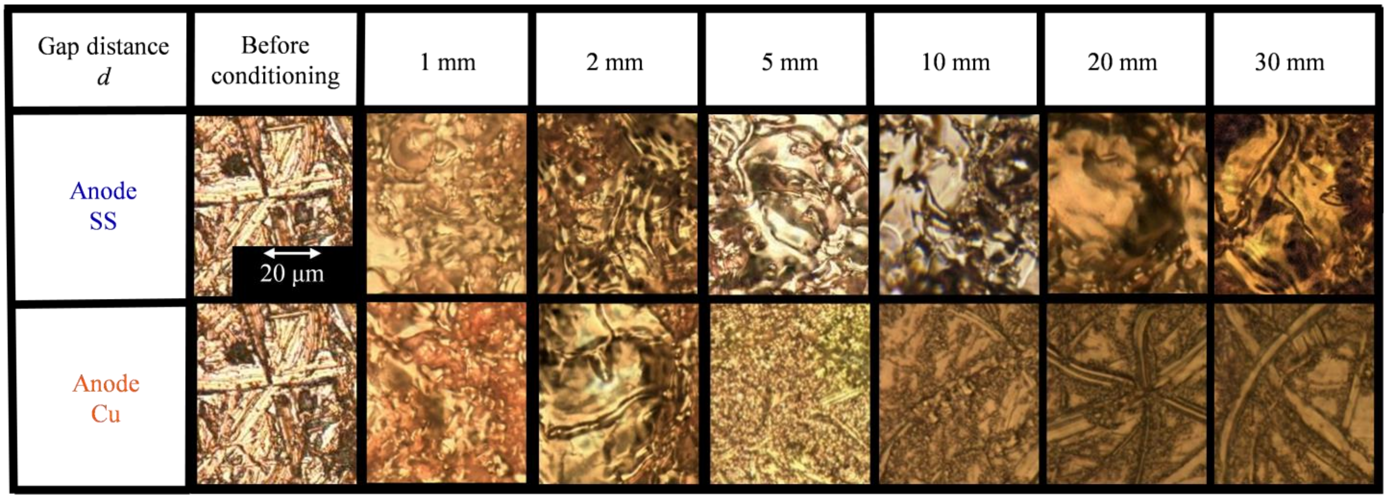


Figure 7. Microscope images of the surface at the tip of the Cu cathode before and after conditioning saturation (r = 2 mm, R_L = 60 Ω).

materials for short gap distances. In addition, when CH-BD mainly occurred, the BD charge was large [6] and the cathode was heavily damaged. In contrast, for long gap distances with the Cu anode, AH-BD tends to occur because a high voltage is needed to form a high electric field; therefore, the electron accelerating voltage between the electrodes becomes large. During AH-BD, it is considered that the cathode temperature immediately prior to BD is lower than that during CH-BD, and the damage to the cathode surface is suppressed. However, for the SS anode, it is thought that CH-BD tended to occur even for long gap distances. This agrees with the heavy damage of the cathode for the SS anode (Figure 7). As mentioned in Section 3.1, this agrees with the decrease in BD voltage during the conditioning (Figure 4) and the concentration of the BD spot at the cathode tip (Figure 5). As a result, V_{sat} for the Cu anode was higher than that for the SS anode where CH-BD mainly occurred (Figure 6).

3.3 EFFECT OF GAP DISTANCE AND ANODE MATERIAL ON BREAKDOWN CHARGE DEPENDENCE

Figure 8 shows the relationship between BD field strength E_{sat} at the cathode tip and charge Q_{BD} per single BD after conditioning saturation. E_{sat} was calculated from BD voltage by using the charge simulation method, and Q_{BD} is the time integration value of the discharge current waveform in a BD after conditioning saturation as shown in Figure 3. The symbols represent the average values for each combination of r and d. The error bars represent the minimum and maximum values of E_{sat} and Q_{BD} after the conditioning saturation.

For the SS anode, E_{sat} depended on Q_{BD} in spite of d and r (Figure 8a) and CH-BD mainly occurred, as discussed in Section 3.2. CH-BD occurred after the cathode temperature reached the melting point, which depended on the electric field at the cathode surface regardless of the applied voltage. The cathode temperature just before BD will have an almost constant value, namely, the melting point [6]. Thus, the amount of molten cathode material or damaging effect of cathode depends only on the discharge magnitude Q_{BD}.

For the Cu anode, the relation between E_{sat} and Q_{BD} depended on d (Figure 8b). For d = 5 mm, AH-BD tended to occur, as discussed in Section 3.2. AH-BD can occur before the cathode temperature gets up to the melting point. In other words, for AH-BD, less of the cathode melted than for CH-BD. The damage to the cathode surface was thereby suppressed, improving the conditioning effect, and V_{sat} increased with Q_{BD}.

For d = 2 mm, CH-BD mainly occurred as discussed in Section 3.2, similar to the SS anode. In Figure 8b, the damage to the cathode surface was dominant at $Q_{BD} \geq 3$ mC. At lower Q_{BD} values ($Q_{BD} \leq 3$ mC), the conditioning progressed more than at higher Q_{BD} values, and E_{sat} increased. This higher E_{sat} could increase the collision energy of the electrons with the anode at BD, and the BD mechanism would change from CH-BD to AH-BD, resulting in the appearance of the maximum E_{sat} in Figure 8b.

Figure 9 shows the dependence of the BD characteristics on the gap distance for AH-BD. For longer gap distances, the voltage accelerating electrons between electrodes became large. Thus, a smaller field emission electron current is sufficient for BD. This means that BD occurs in a lower electric field at longer gap distances. Because the cathode heating before BD is caused by the field emission electron current, the amount of the molten cathode depends on the electric field on the cathode surface. Thus, for longer gap distances, the cathode temperature immediately prior to BD is lower than that for shorter gap distances. Therefore, for AH-BD, the longer the gap distance, the larger the Q_{BD} needed to obtain the maximum E_{sat}.

3.4 OPTIMUM BREAKDOWN CHARGE FOR SPARK CONDITIONING

For AH-BD, at longer gap distances, Q_{BD} to obtain the maximum E_{sat} increased, whereas at shorter gap distances, CH-BD mainly occurred. For CH-BD, the cathode temperature just before BD was constant at the melting point. However, for AH-BD, the cathode temperature did not reach the melting point before BD. Thus, the cathode temperature just before BD for CH-BD was higher than that for AH-BD. This means

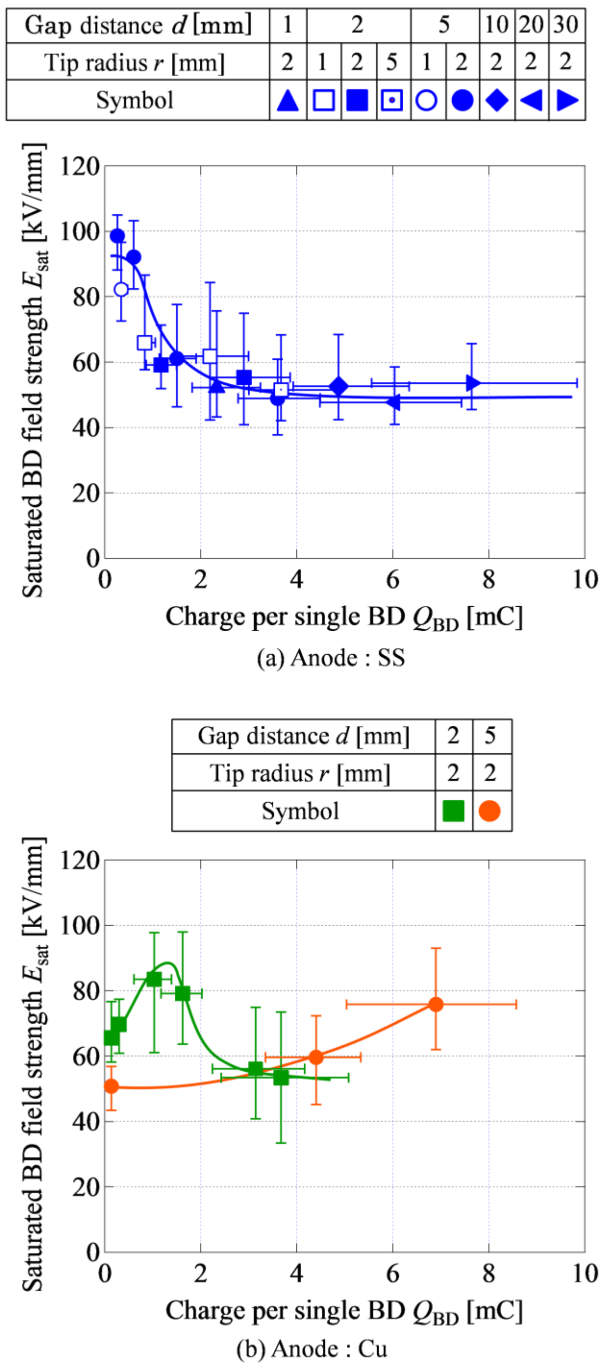


Figure 8. Relationship between E_{sat} and Q_{BD}. The error bars represent the minimum and maximum values after the conditioning saturation.

that for CH-BD the same amount of molten cathode, (and thus the same conditioning effect) could be obtained with a smaller Q_{BD} than for AH-BD (Figure 8). Therefore, E_{sat} reached its maximum value at a smaller Q_{BD} value.

For CH-BD, the cathode temperature just before BD did not depend on the cathode shape (Figure 8a). Therefore, because the amount of molten cathode, which indicates the conditioning effect and the damage to the cathode, depended on Q_{BD} only, and the Q_{BD} value required to obtain the maximum E_{sat} value did not depend on the cathode shape. We

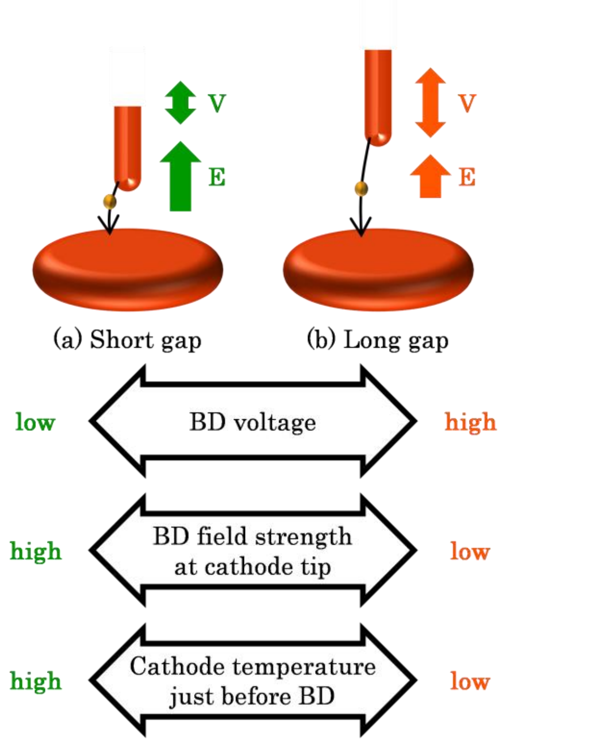


Figure 9. Gap distance dependence of BD characteristics in the case of BD based on anode heating (AH-BD).

expect that these conditioning characteristics should be able to identify the optimal Q_{BD} for the maximum E_{sat} in any electrode configurations.

A previous study showed that the damaging effect during the spark conditioning decreases the minimum BD voltage rather than the 50% BD voltage [9]. In the conditioning of VIs, the minimum BD voltage is as important to reliability as 50% BD voltage is [11]. In this paper, we focused on maximizing E_{sat} to optimize conditioning. However, based on the BD mechanisms, the damage is also dominated by Q_{BD}. Therefore, we expect that our method could also be used to maximize and optimize the minimum BD voltage.

4 CONCLUSION

We focused on the dependence of conditioning characteristics in vacuum on the gap distance and BD charge for various anode materials. Our results for the optimal BD charge for spark conditioning in vacuum to maximize the 50% BD electric field E_{sat} can be summarized as follows:

(1) For short gap distances, CH-BD occurs regardless of the anode materials. Therefore, damage to the cathode surface becomes dominant.

(2) For long gap distances and anode materials with a high melting point, CH-BD mainly occurs. In contrast, for anode materials with a low melting point, AH-BD mainly occurs, and damage to the cathode surface is suppressed.

(3) When AH-BD mainly occurs, the longer the gap distance is, the larger the optimal Q_{BD} to obtain the maximum BD field strength.

(4) When CH-BD occurs, the optimal BD charge to obtain the maximum BD field strength does not depend on the electrode shape.

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