Conditioning Mechanism of Cu-Cr Electrode Based on Electrode Surface State under Impulse Voltage Application in Vacuum

Hiroki Kojima, Naoki Hayakawa
Nagoya University
EcoTopia Science Institute
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Ryouki Nishimura, Hitoshi Okubo
Nagoya University
Department of Electrical Engineering and Computer Science
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Hiromasa Sato, Hitoshi Saito and **Yasushi Noda**
Japan AE Power Systems Corporation
Kokubu-cho, Hitachi, 316-0035, Japan

ABSTRACT

From a viewpoint of high insulation performance and environmental-friendliness, vacuum attracts attention. Vacuum circuit breakers (VCBs) are expected to develop into higher voltage level. In this paper, we discuss the relations between the surface condition and the conditioning mechanism of Cu-Cr electrode during impulse voltage application in vacuum. The experimental results showed that the deposited layer at the cathode surface was formed by the anode material due to the impulse voltage application. In Addition, we investigated the content ratio of cathode and anode material on the surface after saturation of conditioning and relation between BD discharge area and deposited area at electrode conditioning. We finally clarified that under impulse voltage application, cathode surface characteristics were approaching to those of the anode material, however, the ratio between Cu and Cr was different. This means that anode material could determine the final state of conditioning.

Index Terms — **impulse conditioning, vacuum, Cu-Cr, deposited layer, parallel-plane electrode, quasi-uniform electric field, electrode surface.**

1 INTRODUCTION

AN improvement of dielectric strength is required in VCBs and vacuum interrupters (VI) for the use of higher voltage systems [1-3]. Therefore electrode systems are conditioned to get a reliable high electric strength. The impulse conditioning technique is used to achieve a higher voltage, and the clarification of the conditioning characteristic is requested [4-7].

In general, electrode conditioning has been known as the method of improving weak area by melting electrode surface [8, 9], removing adsorption gas of electrode that would cause pre-breakdown current [10, 11]. In addition, the characteristics of cathode surface deeply relate to the field electron emission that can initiate breakdown in vacuum [12]. The anode surface state influences pre-breakdown current by adsorption gas [13]. It was found that the fine dispersion layer could be formed on the electrode surface. The fine dispersion layer improved the material characteristics as enhancement of the BD voltage [14-16]. However, relations between the conditioning mechanism and electrode surface state at conditioning process are still not clear. Therefore, in this paper we investigated the details about the relations between them.

We applied negative standard lightning impulse (LI) voltage under quasi-uniform electric field. We focused on the change of Cu-Cr electrode surface state with the conditioning process and discussed the mechanisms of conditioning process in vacuum.

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2 EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows the experimental set up and the electrode configuration. We used the parallel plane electrodes with the gap length d=5 mm, under quasi-uniform electric field. The negative standard lightning impulse voltage (1.2/50 μs) was applied to the upper electrode. Cu-50wt%Cr or SUS304 electrode with diameter ϕ=22 mm was used for cathode and anode. Four kinds of electrode material combination used in the experiments were shown in Table 1.

For voltage application procedure, we used up-down method from 24.6 kV with the voltage step ΔV = 4.1 kV. The illumination spots on the electrode surface at BD discharge were observed by two digital cameras from two right-angled directions. The electrode surface was observed before and after conditioning process. In addition, after conditioning process, the electrode surface materials were analysed by energy dispersive X-ray spectrometry (EDX). During the conditioning process, the vacuum pressure in the chamber was kept at the order of 10^{-6} Pa.

Figure 2 shows the result of observing the electrode surface by microscope before conditioning process. In Fig. 2, the surface of Cu-Cr electrode has rougher than that of SUS304 electrode. It can be seen Cu and Cr areas exist separately in Cu-Cr electrode.

3 MESUREMENT AND DISCUSSION

3.1 Conditioning history and analysis of electrode surface by SEM and EDX

Figure 3 shows the electrode conditioning histories in four kind electrode systems by up-down method. BD voltages of the all electrode systems were enhanced by lots of impulse voltage applications, reaching saturation. The saturated BD voltages of electrode systems with SUS304 anode are higher than those with Cu-Cr anode. In Fig. 3 (a), the BD voltage history of Cu-Cr/SUS304 electrode system is similar to that of Cu-Cr/Cu-Cr until 1100 times of voltage application. Afterwards, the BD voltage approaches to that of SUS304/SUS304. In Fig. 3 (b), the BD voltage history of SUS304/Cu-Cr depends on Cu-Cr used as the anode material from early stage of the conditioning process. Figure 4 shows the saturated 50% BD voltages in four kinds of electrode material combination. We can see in this figure that their final saturated voltages are highly depended on the anode material.

Figure 5 shows the result of the cathode surface observation by SEM after the impulse conditioning process in SUS304/Cu-Cr. In Fig. 5, the surface was melted by impulse conditioning process and many melted particles can be seen on the cathode surface. The similar situation was also found on the cathode surface in electrode system with SUS304 anode.

Figure 6 shows the results of material analysis by EDX that were examined to a depth of 3 μm from the surface after the conditioning process. The vertical axis is the characteristic

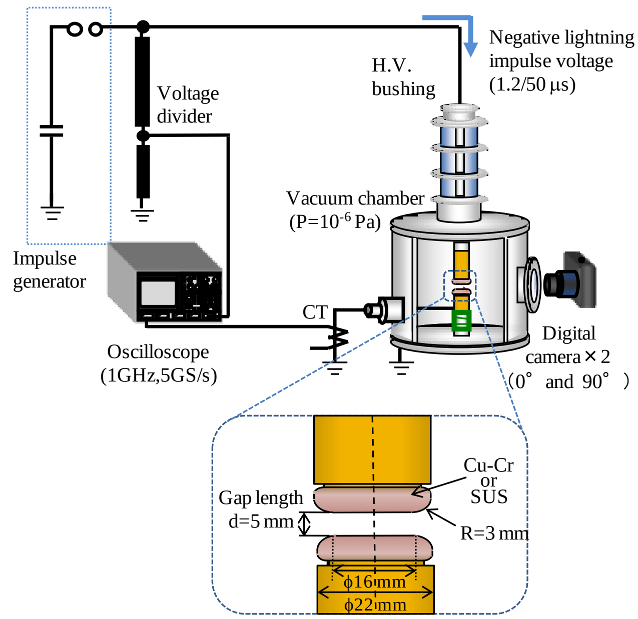
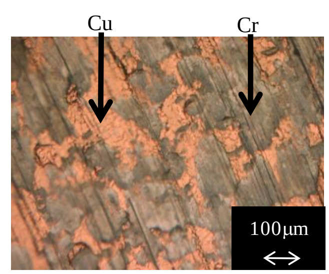


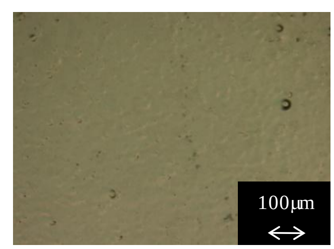
Figure 1. Experimental setup and electrode configuration.

Table 1. Combination of different electrode materials.

Electrode [mm]	Gap [mm]	Cathode material	Anode material
ϕ22	5	SUS304	SUS304
		Cu-50wt%Cr	Cu-50wt%Cr
		Cu-50wt%Cr	SUS304
		SUS304	Cu-50wt%Cr



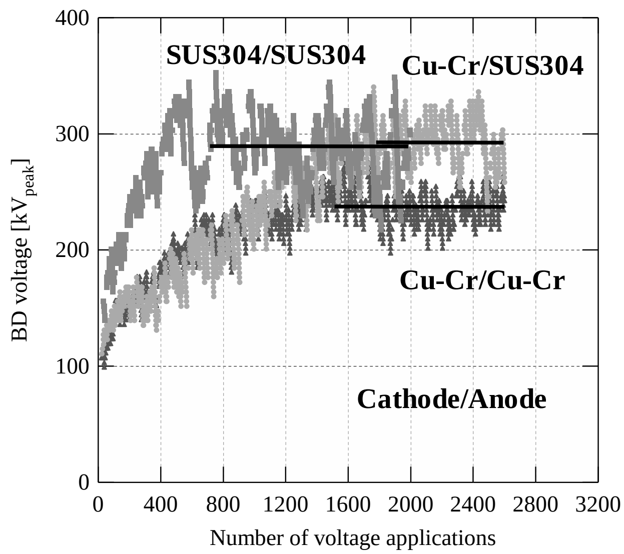
(a) Cu-50wt%Cr, R_a= 1.39μm.



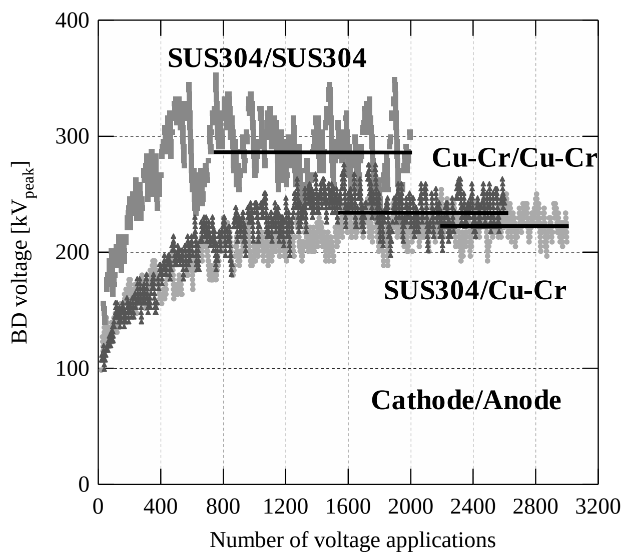
(b) SUS304, R_a= 0.60μm.

Figure 2. Electrode surface before conditioning process.

X-ray intensity ratio of each material to CrKα. In Fig. 6 (a), Fe, Ni and Cr which are major materials of SUS304 were detected at the cathode made by Cu-Cr. On the other hand, in Fig. 6 (b) at the anode, only anode material is detected and cathode material (Cu-Cr) is not detected. Similarly, in Figs. 6 (c) and (d), the material components of anode were detected on the both surfaces of anode and cathode. These results mean that after the impulse conditioning process the cathode surface was covered by the deposition of anode materials and the deposition formed the deposited layer of 3μm or more. Therefore, it is considered that during conditioning process, the material characteristic of cathode surface changes into that of anode surface and the anode material strongly influences the saturated BD voltage as shown in Fig. 4.



(a) Feature of transition of Cu-Cr / SUS304.



(b) Feature of transition of SUS304 / Cu-Cr.

Figure 3. BD voltage history by up-down method for different electrode materials.

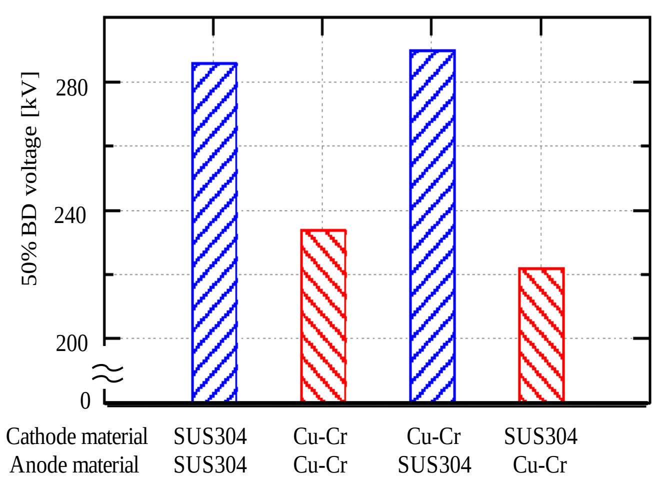


Figure 4. Saturated 50% BD voltages in different combination of electrode material.

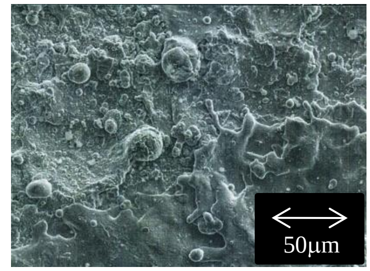
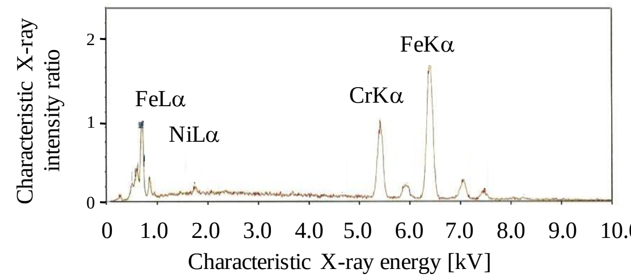
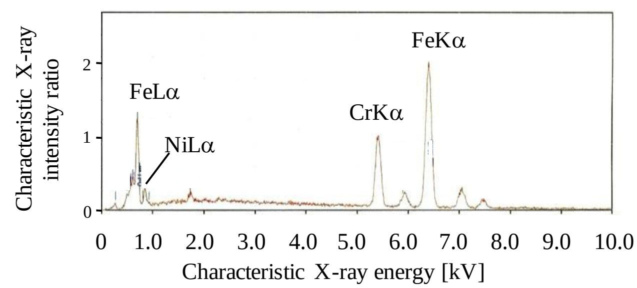


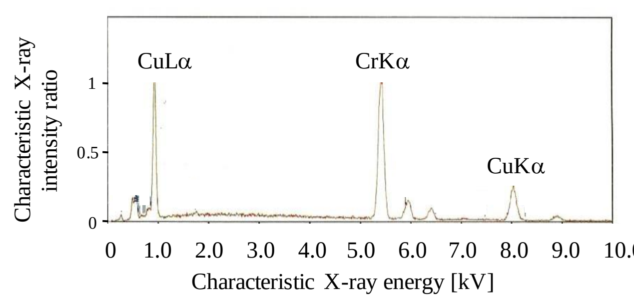
Figure 5. SEM analysis of the cathode surface after conditioning process in SUS304/Cu-Cr.



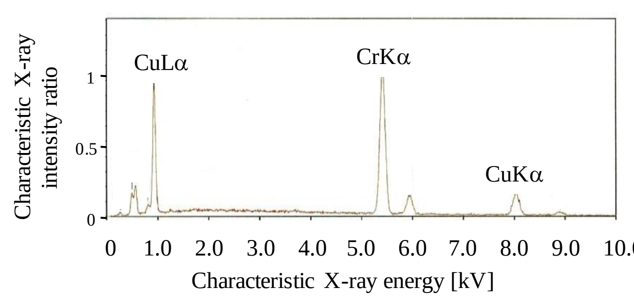
(a) Cu-Cr : Cathode of Cu-Cr/SUS304.



(b) SUS304 : Anode of Cu-Cr/SUS304.



(c) SUS304 : Cathode of SUS304/Cu-Cr.



(d) Cu-Cr : Anode of SUS304/Cu-Cr.

Figure 6. EDX analysis after conditioning process of different electrode material systems.

In addition, we found in a past research that by the impulse conditioning process the fine dispersion layer was formed at the surface of the electrode and that the fine dispersion layer could enhance the withstand voltage [14]. From this fact, we can suppose that the fine dispersion layer correspond to the deposited layer obtained in this paper.

3.2 Content ratio of Cu and Cr on the cathode and anode surfaces after conditioning process

Cathode materials influence the field electron emission that can initiate breakdown in vacuum. In this section, we discuss content ratio of materials (Cu and Cr) on the cathode and anode surfaces after impulse conditioning process. We considered the results of EDX analysis of SUS/Cu-Cr electrode systems shown in Fig. 6 (c), (d). Figure 7 shows the characteristics X-ray intensity ratio of CuLα and CuKα to that of CrKα. From Fig. 7, as for the cathode surface, it can be found that the content ratio of Cu is larger than the ratio of the anode surface. This can be explained as follows. The melting point of Cu (1356K) is lower than that of Cr (2130K), hence relatively lots of Cu would be melted at the anode surface by BD discharge and deposited on the cathode surface. From the above-mentioned result, we clarified that the content ratio of Cu and Cr on the cathode surface after saturation of the conditioning process is different from the ratio on the anode surface. Therefore, it is thought that the content ratio of Cu and Cr in the deposited layer changes by the ratio of initial anode materials.

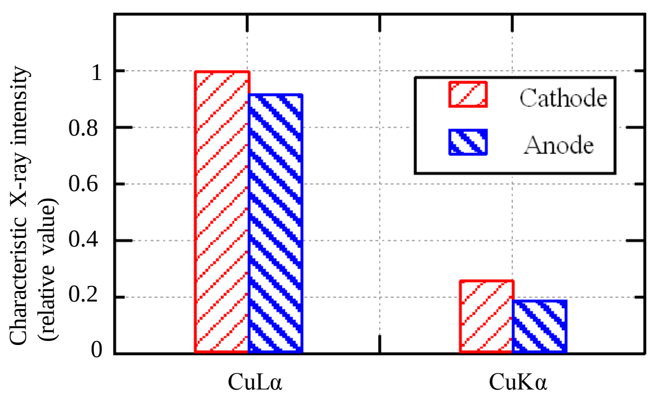


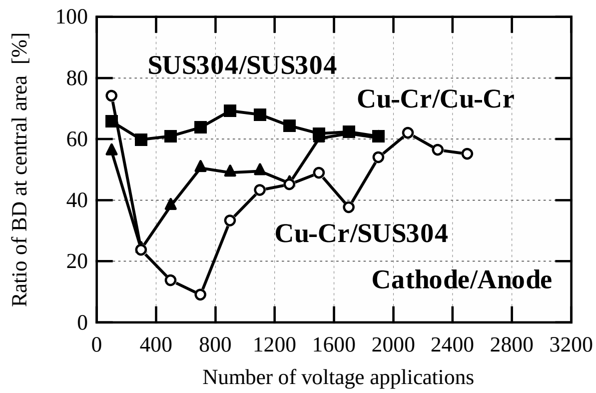
Figure 7. Content ratio of Cu to Cr after conditioning process in SUS304/Cu-Cr.

3.3 Transition characteristics of BD discharge spot area during the conditioning process

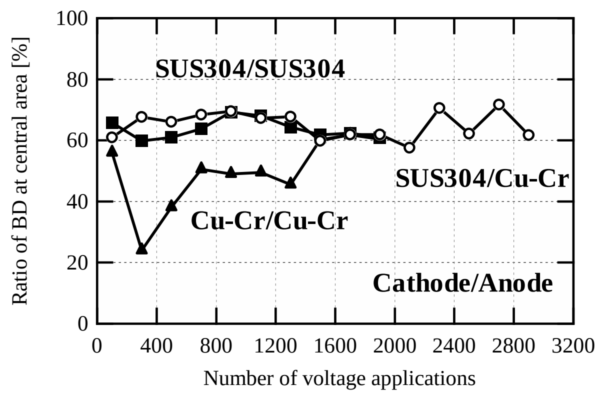
It can be thought that the cause of BD discharge is electron field emission from the cathode. However, from the above-mentioned results, we clarified that the cathode surface state changed greatly by the impulse conditioning process. From this view point, the transition of BD discharge spot area of the impulse conditioning process was examined.

We defined the area within 7.9 mm from the center of the plane electrode, where the electric field is lower than 90% of maximum electric field, as "Central area" of the electrode. Other area is defined as "Edge area" of the electrode.

Figure 8 shows the transition of BD discharge spot area



(a) Feature of transition of BD discharge spot area in Cu-Cr/SUS304.



(b) Feature of transition of BD discharge spot area in SUS304/Cu-Cr.

Figure 8. Ratio of BD discharge at "Central area" for different electrode materials during conditioning process.

ratio in the electrode "Central area" every 200 voltage applications. The conditioning process of electrode surface occurs from "Edge area", because "Edge area" has higher electric field than "Central area". From Fig. 8, it seems that the transition of BD discharge spot area ratio is determined by cathode material. In the electrode systems with SUS304 cathode, BD occurred at the whole of electrode surface during conditioning process. By contrast, BD discharge spot area in the electrode systems with Cu-Cr cathode gradually shifted to the whole of electrode surface after BD discharge concentrated on the edge. Additionally, when BD discharge concentrated on the edge, the deposited layer did not exist on the whole of cathode surface in view of BD voltage history yet. The detailed examination of the electrode surface state at conditioning process is shown in section 3.4.

As shown in Fig. 2, because Cu-Cr electrode has rougher surface than SUS304 electrode, it is considered that conditioning at the edge of Cu-Cr cathode takes lots of impulse voltage applications. Figure 9 shows the minimum ratio of BD discharge at "Central area" during conditioning process. In Fig. 8, in the case of Cu-Cr cathode, because the edge of Cu-Cr cathode takes lots of impulse voltage applications more than that of SUS304 cathode, the minimum ratio of BD at "Central area" is lower. From Figs. 4 and 8, we clarified that the cathode material dominates BD discharge spot at the early stage of conditioning process and anode material can determine the final saturated BD voltage.

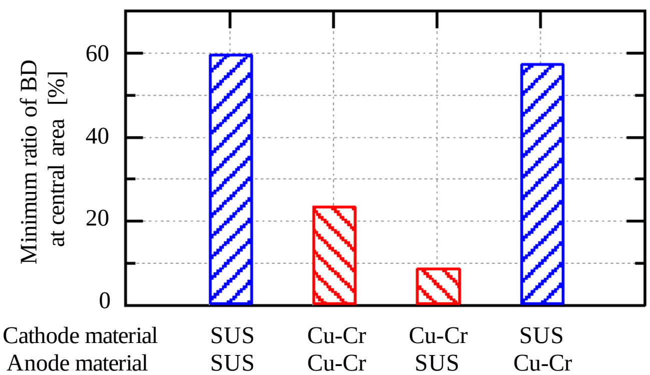
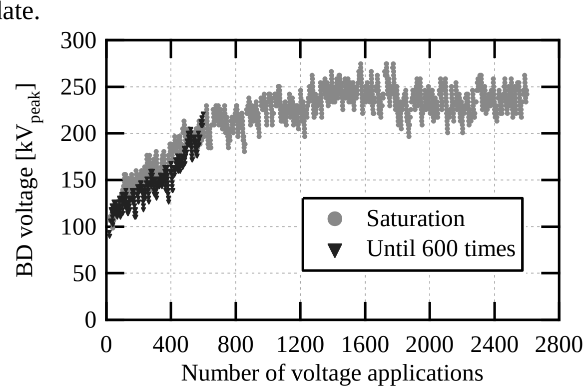


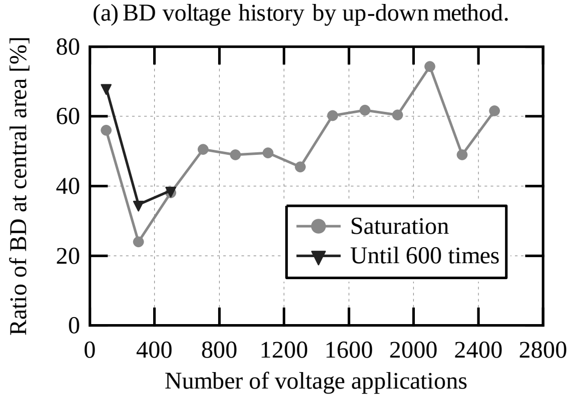
Figure 9. Comparing the minimum ratio of BD at "Central area" in different combination of electrode material.

3.4 Electrode surface in electrode system with Cu-Cr cathode during conditioning process

In this section, we discuss the cathode surface in Cu-Cr/Cu-Cr electrode system during conditioning process. From section 3.3, in electrode system with Cu-Cr cathode, BD discharges concentrate on the edge area at the early stage of conditioning process. Therefore, we applied impulse voltages until 600 times, which corresponds to the number of voltage applications when BD area shifted to the whole of electrode surface. Figure 10 shows the electrode conditioning histories by up-down method and the transition of BD discharge spot area ratio in the central area of electrode. For comparison, the result with saturation of conditioning process is additionally shown. We can confirm the reproducibility of the experiment at date.



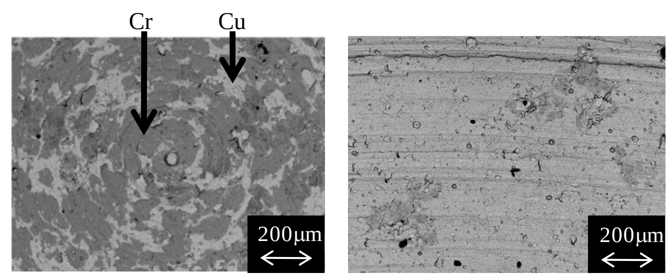
(a) BD voltage history by up-down method.



(b) Transition of BD discharge spot area during conditioning process.

Figure 10. Histories of conditioning process in Cu-Cr/Cu-Cr.

Figure 11 shows the images of Backscattered Electron Image (BEI) observed at central area and edge area on the cathode surface after 600 times of voltage application. In Fig. 11 (a), Cu and Cr exist separately at central area of the cathode. This agrees with the base materials of Cu-Cr electrode shown in Fig. 2. By contrast, at edge area of the cathode shown in Fig.11 (b), the boundary of Cu and Cr is not clear. It is because the base materials were covered by the deposition from the anode to the cathode. In fact, when BD discharges concentrate on the edge area of electrode, the deposited layer is formed only on the edge area, not formed on the central area. Therefore, the withstand voltage in the edge area is strongly enhanced, the withstand voltages of edge and central area become the same extent. BD discharge spot area gradually shifted to the whole of electrode surface from the edge area. It is thought that the deposited layer of the central area is formed at the late stage of conditioning process.



(a) Central area. (b) Edge area.

Figure 11. BEI analysis of the cathode surface after 600 times of voltage application in Cu-Cr/Cu-Cr.

4 CONCLUSIONS

In this paper, we investigated the Cu-Cr electrode surface state and the BD conditioning mechanism under quasi-uniform electric field in vacuum. As a result, we found the following characteristics of conditioning.

1. After impulse conditioning process, the cathode surface is covered with thickness of 3μm or more by the anode material. Therefore, characteristics of cathode surface change into those of anode material due to the deposited layer during conditioning process.
2. In electrode system with cathode: SUS304 and anode: Cu-Cr, after saturation of conditioning process, the content ratio of Cu at the cathode surface is larger than the ratio at the anode surface.
3. In electrode systems with Cu-Cr cathode, because surface of the Cu-Cr electrode has rough, conditioning at the edge area of Cu-Cr cathode takes lots of impulse voltage applications. Therefore, in the early stage of conditioning process, BD discharges concentrate on the edge area of electrode.
4. In the early stage of conditioning process, initial surface state of cathode dominates BD discharge spot. On the other hand, after saturation of conditioning process, the characteristics of anode material can determine the final saturated BD voltage.
5. In electrode systems with Cu-Cr cathode, when BD discharges concentrate on the edge area of electrode, the deposited layer is formed only on the edge area.

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Hiroki Kojima was born on 7 December 1975. He received the Ph.D. degree in 2004 in energy engineering and science from Nagoya University. Since 2004, he has been at Nagoya University and presently he is an Associate Professor of Nagoya University at the EcoTopia Science Institute. Dr. Kojima is a member of IEE of Japan.

Ryouki Nishimura was born in Mie, Japan in 1986. He received the B.E. degree in electrical engineering in 2010 from Nagoya University. Currently, he is a Master Course student of Nagoya University at the Department of Electrical Engineering and Computer Science.

Naoki Hayakawa (M'90) was born on 9 September 1962. He received the Ph.D. degree in 1991 in electrical engineering from Nagoya University. Since 1990, he has been at Nagoya University and presently he is a Professor of Nagoya University at the EcoTopia Science Institute. From 2001 to 2002, he was a guest scientist at the Forschungszentrum Karlsruhe/Germany. Prof. Hayakawa is a member of CIGRE and IEE of Japan.

Hiromasa Sato was born on January 1982. He received the B.S. degree in 2006 in physics from Nihon University. Presently he works at Research and Development Division in Japan AE Power Systems Corporation, Japan. Mr. Sato is a member of IEE of Japan.

Hitoshi Saito was born on 29 June 1970. He received the B.S. degree from Hokkaido University, Japan in 1995 and the Ph.D. degree in electrical engineering from Nagoya University, Japan in 2002. He joined Meidensha Corporate Ltd, Japan in 1995. Presently, he works in research of VCBs at Japan AE Power Systems Corporation, Japan.

Yasushi Noda was born on February 1952. He received the B.E. degree in 1974 in mechanical engineering from Tokyo University of Science. Presently he works at Research and Development Division in Japan AE Power Systems Corporation, Japan. Mr. Noda is a member of IEE of Japan.

Hitoshi Okubo (M'81) was born on 29 October 1948. He received the Ph.D. degree in 1984 in electrical engineering from Nagoya University. He joined Toshiba Corporation, Japan in 1973 and was a manager of high voltage laboratory of Toshiba. From 1976 to 1978, he was at the RWTH Aachen, Germany and the TU Munich, Germany. In 1989, he was an Associate Professor and presently he is a Professor of Nagoya University at the Department of Electrical Engineering and Computer Science. He is a member of IEE of Japan, VDE and CIGRE.