Generation of Low Frequency Atmospheric-Pressure Uniform Discharge in Air

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Abstract: We found that a generation of APTD (Atmospheric-Pressure Uniform Discharge) was possible at a frequency range of 32Hz to 1kHz by using alumina as a barrier material of a DBD device. In order to clarify the mechanism of the generation of the low frequency APTD, we investigated the influence of ambient gases and barrier materials. From these experiments, we found that gaseous species are not a decisive factor of the generation of the APTD, but the barrier material is playing an important role for the stable generation of the low frequency APTD.

Keywords: Dielectric Barrier Discharge, Atmospheric Pressure, Uniform Discharge, APTD.

1. Introduction

The Dielectric Barrier Discharge (DBD) is composed of many filamentary micro discharges, and it can be applied to ozone generation [1], NOx removal from exhaust gas [2] and so on. In 1988, a group of Sophia University found that a stable Atmospheric-Pressure Glow Discharge (APGD) could be generated in helium [3]. They reported that there are three conditions to generate the stable APGD: they are (1) use of a frequency higher than 1kHz, (2) insertion of a dielectric barrier at least on one of the electrodes, and (3) use of helium as dilution gas [4]. The APGD has a great potential for uniform surface treatment [5], photo-resist etching [6] and so on. Therefore, many researchers have investigated various methods to generate the APGD or an uniform discharge in air or in other gases. As the results, it was found that uniform discharges can be generated in pure nitrogen gas using a kHz order AC power source [7, 8]. They concluded that the uniform discharge in pure nitrogen gas can be generated if there are enough seed electrons to turn on the discharge under a low electrical field. These seed electrons are mainly created by the Penning effect due to collisions between two nitrogen metastables. However, as H and O atoms quench nitrogen metastables, the existence of H and O atoms makes the generation of the uniform discharge difficult. Therefore, so far, it was a common sense among scientists that the generation of the uniform discharge in the gases containing O₂ was very difficult. As far as we know, generation of the uniform discharge in air in a low frequency region with a simple DBD device has never been reported.

In this paper, we report that the use of ceramics as barrier material generates the low frequency atmospheric pressure uniform discharge in air and in other gases.

2. Experimental setup

The experimental arrangement of this study is shown in Fig. 1. The DBD devise is set in air, nitrogen, oxygen or helium gas at atmospheric-pressure. Gas is circulated in the gap between the dielectric plates by use of a gas circulator. The barrier material is alumina (Kyocera A473), and its size and thickness are 100cm² and 1mm respectively. The gap length was fixed to 1.95mm. AC high voltage was applied to the DBD device by a step-up transformer. Frequency of the applied voltage ranges from 10 to 1 kHz, and the maximum applied voltage was 42kVp-p. The applied voltage and discharge current were measured by an oscilloscope (Tektronix 2024B, 100MHz, 2.0GS/s) using a H.V probe (Pulse Electronic Engineering, EP-50K, 1/2000) and a shunt resistor (1kΩ) respectively.

Pictures of a low frequency uniform discharge were taken by a digital camera (Nikon D200) with/without an image intensifier (Hamamatsu Photonics Model-C5100 (Night viewer)). The gap voltage during discharge was calculated from the difference of voltages applied to the discharge device and to the barrier plates. The electrical field strength in the gap was calculated from the gap voltage and gap length [9]. Besides, an integral of the discharge current (charge) was measured by measuring the voltage of a series (integral) capacitor.

Fig. 1 Experimental setup
3. Experimental results and discussions

3.1 Electrical characteristics of uniform discharge

Fig. 2 shows a time evolution of the applied voltage and the current of the barrier discharge in air at 50Hz. As it is seen in the figure, the discharge current has only one peak in a half cycle. The electrical field strength in the gap during discharge was around 3.2kV/mm (=6.3kV/1.95mm) which corresponds to the breakdown electrical field strength in air at atmospheric pressure. Fig. 3 shows the discharge photographs. We observed stable homogeneous discharges at the applied voltages lower than 13.4kVp. These uniform discharges seem to be the APTD which was reported by N. Naudé et al. [10], because the gap voltage and discharge current waveforms are very much like the figures shown in the paper. However, when an applied voltage becomes higher than 13.8kVp, the discharge changed from the APTD mode to a non-uniform pulse mode as shown in Fig. 3. Fig. 4 shows the current and applied voltage when the discharge changed to a pulse mode. It is interesting to note that the gap voltage abruptly increased just before the current became pulsatile. Fig. 5 shows an enlarged waveform of the pulse current. The waveform is represented by the following equation.

\[ i = i_d - (i_{\text{max}} - i_d) \cdot e^{-t/\tau_2} \]

where \( i_d \) is the displacement current, \( i_{\text{max}} \) is an initial value of the discharge current, and \( \tau_1 \) is a time constant.

The pulse current changes with two time constants, namely \( \tau_1 = 4 \mu s \) and \( \tau_2 = 1 \mu s \).

There is a domain of generation of the stable APTD, which is shown in Fig. 6. We confirmed that the lower limit voltages in a domain correspond approximately to the breakdown voltage in air, and the upper limit voltage increases in proportion to the power frequency. At frequency higher than 80Hz, we could not confirm the upper limit voltage, because breakdowns occurred between outer electrodes. However, at 15kVp, we observed stable generations of the APTD at any frequency between 80 Hz and the maximum power source frequency of 1kHz.

In order to make clear why the discharge mode changed from the APTD mode to a pulse mode, we observed the discharge current more carefully. Fig. 7 shows enlarged discharge currents. It is seen that near the upper limit voltage (13.8kVp), the discharge current began to increase clearly at around 8.5ms, but it turned to decrease at 9.5ms. The discharge current then began to increase rapidly at 10.5ms and became an uniform discharge. Such a decrease of the current before the uniform discharge was not observed in the case of medium and lower limit voltage. On the other hand, when the discharge changed to a pulse mode at the voltage just above the upper limit, the pulse current became 200 to 700 times larger than the current of APTD mode, and the pulse current began to flow about 1.02ms earlier than that of the case of APTD mode. Fig. 8 shows the electrical field strengths. In the
In the case of the APTD mode, the electrical field strength of the gap gradually increased and attained around 3.5kV/mm. However, in the case of pulse mode, the electrical field strength of the gap abruptly increased from 1.2kV/mm to 3.0kV/mm at 9.3ms. A discharge started at the instance, and then perhaps due to pulse current flow, the electrical field strength of the gap oscillated. Fig. 9 shows the enlarged voltage and current in the case of pulse mode. It is seen that the current began to increase slightly at -14.4µs and it attained to -4mA at around 0µs. The discharge current then began to increase drastically in an oscillation mode. It is quite different from the discharge current of the APTD mode at the upper limit voltage. Because the slight decrease of the current just before the discharge start is not observed.

### 3.2 Influence of ambient gas

There are papers that described the mechanism of the APTD generation. They reported that a nitrogen metastable is important for the generation of the APTD [7, 8], and the existences of H and O atoms make the generation of the APTD difficult, because they quench nitrogen metastables. O₂ molecules capture electrons by the electronegative property. Therefore, we investigated whether our APTD could generate in O₂, N₂ and He gases. Fig. 10 (a) - (c) show the applied voltage, gap voltage and current of the discharge in these gases. The applied voltages were just below the upper limit voltage. Because the discharge currents show only one peak in a half cycle, it is considered that the uniform discharge generated in all gas tested. Here, it is a remarkable finding that a uniform discharge was observed even in O₂, because it has never been reported. The breakdown electrical field strength of O₂, N₂ and He are 2.9kV/mm, 3.4kV/mm and 356V/mm respectively. Fig. 11 (a) - (d) show photographs of dis-
charges in these gases. In case of O₂ and He gases, an exposure time was extended to 30s and 10s respectively, because light emissions from O₂ and He gases were very weak. We can see that the discharges are uniform and the luminescence near the barrier surface is brighter than that in the center of discharge. As our uniform discharge generated without depending on gas species, it is considered that the uniform discharges generated due to the special function of the barrier surface.

3.3 A combination of different barrier materials
We conducted discharge experiments on DBD device using a combination of soda-glass and alumina. Fig. 12 shows an oscillogram of this experiment. It is interesting to see that different discharge mode appeared in each half cycle. It was confirmed that the uniform mode appeared when the alumina barrier becomes a cathode. Fig 13 shows discharge photographs. The left figure shows discharge in the half cycle when the alumina barrier becomes cathode. The luminescence gradually increased from alumina to soda-glass and a strong luminescence appeared on the soda-glass barrier surface. It is considered that the released electrons from the alumina barrier surface or secondary electrons by the collision of positive ions to the alumina barrier surface are accelerated to the opposite direction by an electrical field, and the electron avalanche (Townsend discharge) occurred.

4. Conclusions
We found that a barrier discharge device using alumina as barrier material can generate an uniform APTD in air, O₂, N₂ and He gas at a frequency range of 32Hz to 1kHz. We also found that there is a domain in frequency and voltage, where the stable APTD generates. The upper limit voltage, when the discharge transferred to pulse mode, increases with a frequency. We had a conclusion that the gas species are not a decisive factor of the generation of the APTD, but a barrier material is playing an important role for the stable generation of the APTD.

References