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Production of Atmospheric Pressure Glow Discharge Using Semiconductor Opening Switch Diode

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An atmospheric pressure glow discharge was generated using a needle-array electrode in nitrogen, and the voltage-current characteristics of the glow discharge were obtained in a range from 1 mA to 60 A. A pulsed high-voltage with short rise time under 10 ns was used to generate homogeneous streamer whole discharge space simultaneously, which prevent the glow-to-arc transition caused by inhomogeneous thermalization. Semiconductor opening switch diodes were employed as opening switch to shorten the rise time. The glow voltage was almost constant until the discharge current became 0.3 A, whereas the voltage increased with the current higher than 0.3 A. Electron density and temperature in a positive column of the glow discharge at 60 A were obtained to $1.4\text{x}10^{12}$ cm^{-3} and 1.3 eV from calculation based on nitrogen swarm data.
Key words: Atmospheric pressure, Glow discharge, Semiconductor opening switch, Pulsed power, Glow-to-arc transition, Nitrogen.

1. INTRODUCTION

Research on atmospheric pressure glow discharges (APGD) is motivated by applications such as instantly activated reflectors and absorbers for electromagnetic radiation, surface modification, thin film deposition, dry etching, remediation and detoxification of gaseous pollution, sterilization, and light sources as gas lasers and excimer radiation [1]-[5]. Much of the efforts in generating stable glow discharges at atmospheric pressure have focused on preventing the onset of instabilities, particularly in the region close to the cathode, because of high electric field and consequently high power deposition compared to that in the positive column of the discharge [6].

A pulse voltage on preventing the thermal instability is commonly employed in the laser community to generate the pulsed glow discharges operated at current densities above threshold for the glow-to-arc transition [7]. This paper describes the generation of APGD in nitrogen gas using pulsed power supply which can generate pulse voltage consisted of a narrow over-voltage pulse and a long width pulse. A needle-array electrode instead of planar electrode was used to generate streamer discharges homogeneously between the electrodes and to keep the glow discharge stable for long duration. The properties of the APGD plasma such as voltage-current (V-I) characteristics, an electron density and an electron temperature are also described.

2. EXPERIMENTAL SETUP

A schematic diagram of the experimental facilities is shown in **Fig. 1**. The grounded electrode plate with rounded edges is made of brass and set in the discharge chamber. The overall diameter and thickness of the electrodes are 10.7 cm and 1.5 cm, respectively. The needle-array electrode made of brass is set to the upper part of the chamber. The needle-array electrode consists of 331 needles which have a dimension of 1.3 cm in height and 50 μm in radius of the tip. Typical gap length *d* from needle tip to the electrode surface is 1.0 cm. The discharge chamber is evacuated with a rotary pump and is filled with the nitrogen gas to atmospheric pressure.

The power supply consists of 8.0 nF capacitor *C*, gap switch, 20 μH inductor *L* and semiconductor opening switch (SOS) diode. The capacitor *C* is charged up negatively to the voltage V_0 using a DC high voltage power supply. The charges are released from the capacitor by switching-on the gap switch mechanically, as the results, the current flow to the LC circuit through the SOS diode as forward-pumping current [8]. After the current direction reverses with LC oscillation, the reverse current is injected into the SOS. With the current interrupted by the SOS, the high voltage pulse is applied to the needle-array electrode as a short nanosecond pulse. **Figure 2** shows the typical waveforms of the circuit current I_0, the capacitor voltage capacitor V_C, and the output voltage V_{out} which is measured at point of V_d shown in Fig. 1 without connecting to the discharge load. This nanosecond pulse produces the streamer discharges from all needle tips simultaneously. The streamer discharges are followed by the glow discharge with the charge remained in the capacitor *C* as shown by V_C in Fig. 2. The current and voltage are measured with

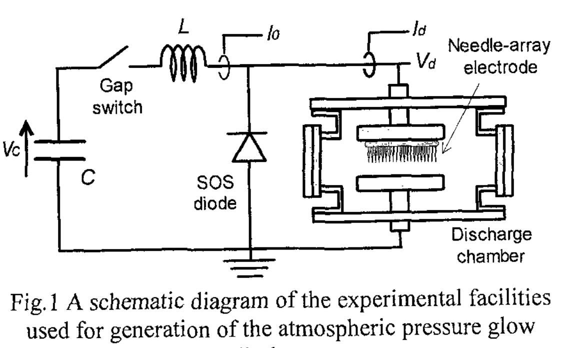

Fig. 1 A schematic diagram of the experimental facilities used for generation of the atmospheric pressure glow discharge.

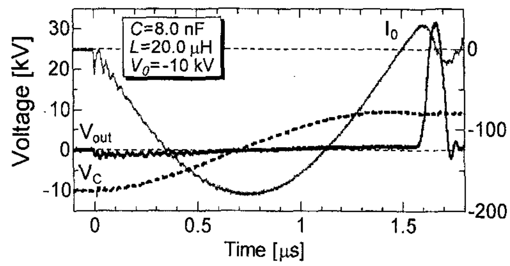

Fig.2 Typical waveforms of circuit current and voltages of the capacitor and the semiconductor opening switch diode at -10 kV charging voltage.

Pearson 2878 current transformers and Sony-Tektronix high-voltage P6015A probes. The signals stored in a digitizing oscilloscope Tektronix TDS3054B are transmitted to a personal computer through a GP-IB cable in order to calculate the energy consumed in the discharge.

3. EXPERIMENTAL RESULTS

3.1 Glow-to-arc transition

Representative waveforms of the transient glow discharge current and the voltage between the electrodes for three different charging voltages are shown in **Fig. 3**. When the narrow over-voltage pulse is applied to the needle-array electrode, the breakdown occurs and the discharge current rises rapidly. The long pulse voltage, which has an altitude of the voltage lower than charging voltage, follows the over-voltage pulse and keeps the glow discharge in a quasi-stable state, *i.e.* a transient glow phase. The glow discharge is sustained for 3 μs at -10 kV charging voltage as shown in Fig. 3(a) with glow current from 10 A to 3 A. At the time of 3 μs, the voltage collapses to a few hundred volts with glow-to-arc transition characterized by an appearance of a luminous spot on the cathode surface [6]. Figure 3 clearly shows that the quasi-stable state glow discharge current increases with increasing the charging voltage

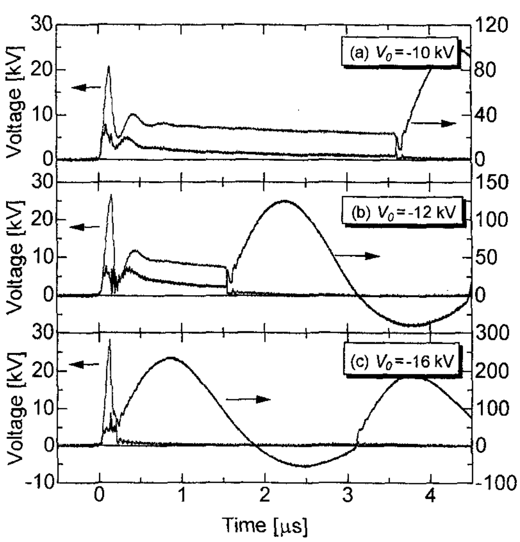

Fig.3 Voltage and current waveforms of the discharge for three different charging voltages. (C: 8 nF, L: 20 μH)

whereas the duration of the glow phase decreases.

Figure 4 shows the transient glow duration as a function of charging voltage at various gap lengths. Clearly, the glow duration increases with reducing charging voltage and with increasing gap length. This result is due to the fact that energy fed into the discharge increases with the charging voltage and/or decreasing gap length. It was previously reported that the duration of a transient glow discharge of 3– 15 A in nitrogen at pressures of 40–130 Torr is independent of gap length in a range of 0.2 to 7.0 mm [9]. This conclusion disagrees with the present result in which the glow duration depends on the gap length. The criterion for the glow-to-arc transition appears to be a certain quantity of surface density of the dissipated energy [10]. The power density on the cathode ϕ is given by

$$\phi = jV_K \qquad (1)$$

where V_K is cathode fall voltage. The current density j can be obtained by dividing glow current by the cathode area. Under the present experimental conditions the glow current increases with gap length as shown in **Fig.5**. This means that the power density ϕ increases with the gap length. However, under the conditions of the previous work, the power density ϕ is dependent on the gap length due to the constant current density which is in agreement with the formula, $j = 400\times10^{-6}p^2$ A cm^{-2} for

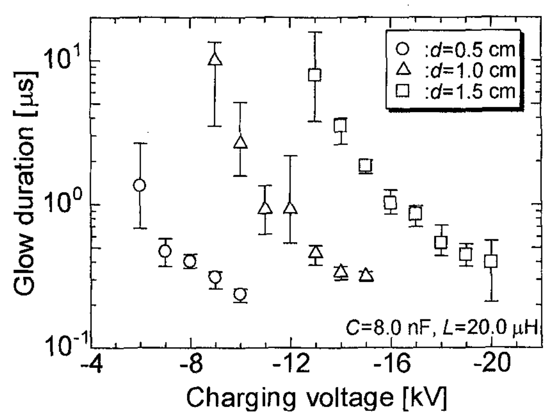

Fig.4 Glow phase duration as a function of charging voltage for three different gap lengths.

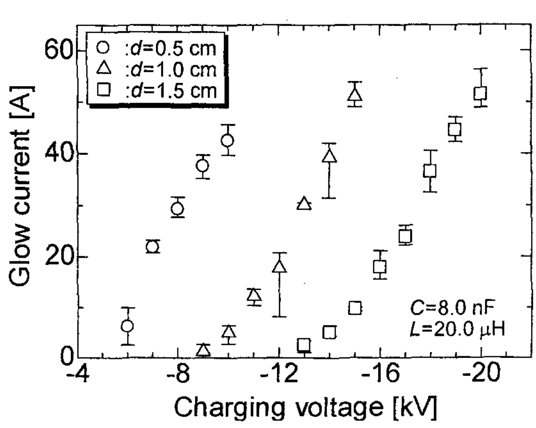

Fig.5 Glow current as a function of charging voltage for three different gap lengths.

low-pressure normal glow discharge [7]. Thus the difference which exists in the previously reported dependence of the transient glow duration on the gap length may be explained by the different dependences of the dissipated power density on the gap length between the two investigations.

3.2 Criterion for the glow-to-arc transition

Chalmers suggested that the criterion for a glow-to-arc transition is that a certain quantity of energy is consumed in the gap during the glow phase [11]. **Figure 6** shows the plots of the energy consumed in the discharge during the glow phase as a function of charging voltage for three different gap lengths. The consumed energies are calculated with time-integration of the power, which is obtained by multiplying the discharge current with the voltage, during the time duration of the glow phase. The consumed energies are almost independent on the charging voltage though the measured values are scattered. The mean value of the consumed energy increases with increasing the gap length, 0.07 J, 0.17 J, and 0.37 J for 0.5, 1.0, and 1.5 cm in gap length, respectively. These values of the consumed energy can be used as a criterion for a glow-to-arc transition [6], [11]. The energy input to the discharge can be changed with the capacitor *C*, the inductor *L*, and/or inserting a damping resistor into the circuit in series. **Figure 7** shows the photographs of atmospheric glow discharge at -10 kV charging voltage. The gap length is 1.0 cm. The capacitance and the inductance are chosen to 4.2 nF and 12.6 μH, respectively, to satisfy above mentioned criterion as shown in Fig. 6. The glow discharges were generated with repetition rate of 50 Hz and the photographs were taken with exposure time of one second. The glow discharge successfully occurs without glow-to-arc transition as shown in Fig. 7. The glow discharges develop from all tips of the needle.

3.3 Voltage-current characteristics

A lot of processes in a direct current glow plasma are governed by the V– I characteristics of the discharge [12]. The V-I characteristics of a transient glow discharge can be obtained in wide current range from milliamps to larger than 100 A using the discharge current and the voltage waveforms [13]. **Figure 8** shows

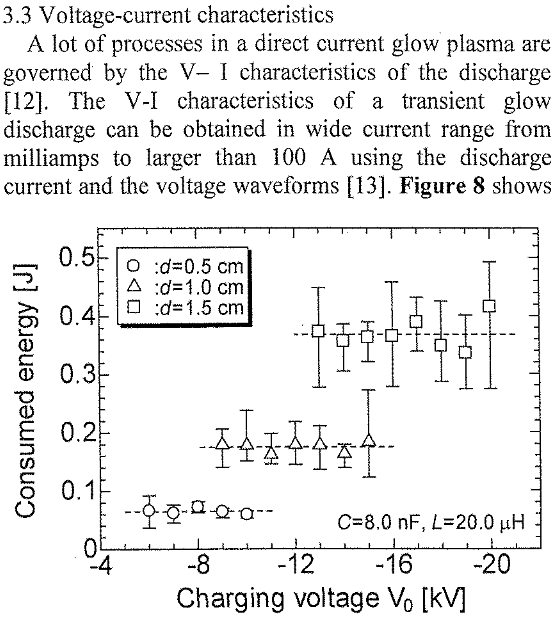

Fig.6 Consumed energy for glow-to-arc transition as a function of the charging voltage for three different gap lengths.

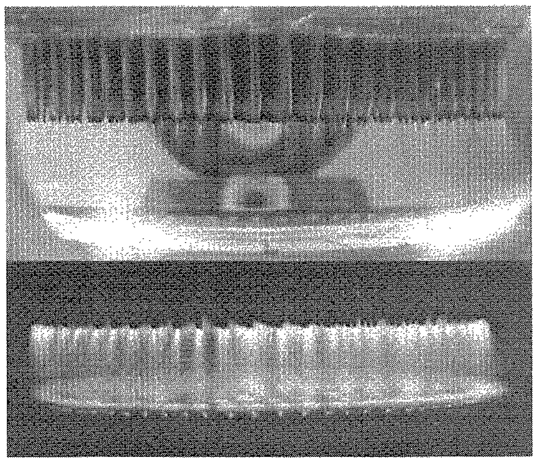

Fig.7 Photographs of atmospheric-pressure nitrogen glow discharge at 1.0 cm gap length. (*C*: 4.2 nF, *L*: 12.6 μH)

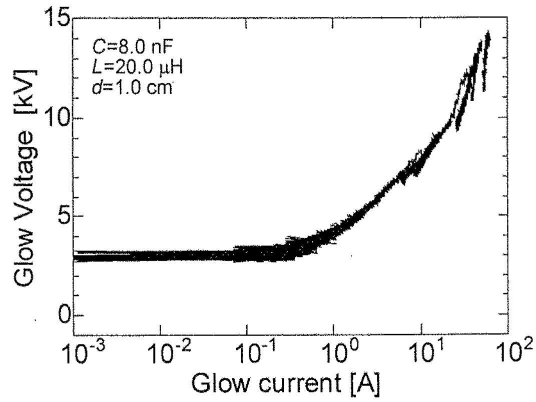

Fig.8 Current-voltage characteristics of nitrogen glow discharge at 1.0 cm gap length.

the V–I characteristics of the quasi-stable glow discharge in atmospheric pressure nitrogen gas at 1.0 cm gap length obtained in the same manner. The capacitance and the inductance are adopted as 8.0 nF and 20.0 μH, respectively. The lines were overwritten at different charging voltage in order to obtain in wide current range. The glow voltage is almost constant, 3 kV, when the glow current is lower than 0.3 A. This independency of the voltage on the current is typical feature of a normal glow discharge [13]. The glow voltage increases from 3 kV to 14 kV with increasing glow current from 0.3 A to 60 A. The glow voltage is almost constant at lower current than 0.3 A while it increases with increasing current in a range larger than 0.3 A. This fact implies that the discharge changes from a normal glow to an abnormal glow at the discharge current of 0.3 A.

3.4 Electron density and temperature

The value of electric field in the positive column of the glow discharge can be predicted from glow voltage and cathode fall voltage, which is determined by "zero length voltage" extrapolating the potential distribution across glow discharge to zero gap length [14]. **Figure 9** shows the plotted gap voltage just prior to the

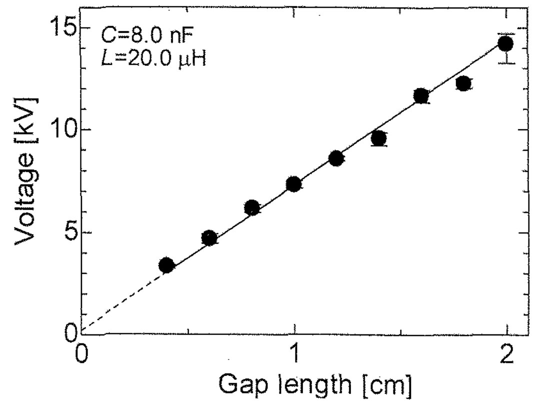

Fig.9 Glow voltage as a function of gap length for nitrogen atmospheric glow discharge.

glow-to-arc transition as a function of the gap length. The gap voltage decreases linearly with reducing gap length. The extrapolation of the potential distribution to zero gap length results in a voltage drop equal to 210 V, which is almost agree with the low-pressure data base [15]. In the normal glow mode (<0.3 A), the electric field of the positive column is roughly obtained to be 2.8 kV/cm, which is consistent to$1.1\text{x}10^{-16}$ Vcm^2 in reduced electric field *E/N*. The electron temperature Te can be calculated from swarm parameters of electrons in nitrogen as well-known Einstein's equation,

$$k_B T_e / e \approx D_e / \mu_e \qquad (2)$$

where μ_e, k_B and D_e are drift mobility, Boltzmann constant (1.38×10^{-23} JK^{-1}) and the diffusion constant, which can be expressed as a function of *E/N* [16]. As the results, the electron temperature is predicted to be 0.9 eV for the normal glow and 1.3 eV for abnormal glow at 60 A in glow current. The averaged electron density in the positive column can be estimated using formula,

$$N_e = j / eW \qquad (3)$$

where *j*, *e*, and *W* are current density, electron charge, and electron drift velocity, which also can be calculated as a function of *E/N* [16]. The current density j in the abnormal glow mode is determined by division of the total glow current by the cross section of the positive column; we assumed the cross section to 42.7 cm^2, which was the area of outline of needle-array positions. As the results, the electron densities are calculated to be $0.8\text{x}10^{10}$ cm^{-3} for normal glow (<0.3 A) and to be $1.4\text{x}10^{12}$ cm^{-3} for abnormal glow at 60 A in glow current.

4. CONCLUSION

The atmospheric pressure glow discharge was generated using a needle-array electrode in nitrogen, and the voltage-current characteristics of the glow discharge were obtained in a range from 1 mA to 60 A. The results show the glow voltage was almost constant until the discharge current became 0.3 A, whereas the voltage increased with the current higher than 0.3 A. Electron density and temperature in a positive column of the glow discharge at 60 A were obtained to $1.4\text{x}10^{12}$ cm^{-3} and 1.3 eV from calculation based on nitrogen swarm data.

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