Evolution of Striation in Pulsed Glow Discharges*

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Abstract In this work, striations in pulsed glow discharges are studied by experiments and Particle-In-Cell/Monte Carlo Collision (PIC/MCC) simulation. The spatio-temporal evolution of the potential and the electron energy during the discharge are analyzed. The processes of striation formation in pulsed glow discharges and dielectric barrier discharges (DBD) are compared. The results show that the mechanisms of striation in pulsed DC discharge and DBD are similar to each other. The evolution of electron energy distribution function before and after the striation formation indicates that the striation results from the potential well of the space charge. During a pulsed breakdown, the striations are formed one by one towards the anode in a weak field channel. This indicates that the formation of striations in a pulsed discharge depends on the flow of modulated electrons.

Keywords: striation, pulsed discharge, PIC/MCC

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(Some figures may appear in colour only in the online journal)

1 Introduction

Striation, known as stratified instabilities, is one of the most common gas discharge phenomenon, mainly shows several bright and dark intervals in the positive column of the discharge. Striation phenomena is usually considered as the consequence of ion-acoustic and ionization waves, and has been observed in many discharge plasmas such as gas laser, fluorescent lamp, plasma jet, and semiconductor manufacturing [1-3], which may result in an unstable discharge or non-uniform processing. On the other hand, this longitudinal instability is also a typical non-linear phenomenon in gas discharge systems. Understanding the mechanism and characteristics of striation formation is important both for achieving stable and uniform discharge plasma and for the fundamental physics in non-linear systems. Striations are also observed in dielectric barrier discharge (DBD) systems, especially reported in the researches of plasma display panel cells [4-5]. In DBDs, striations appear in a wide range of pressure, from low pressure up to atmospheric pressure [6]. The characteristics of striations in DBD obey well the classical similarity laws [7]. The explanation for formation mechanism at low pressure DC glow discharge therefore seems not valid for DBD. Although the mechanism of striation has been studied through experimental and theoretical methods since firstly described by M. Faraday in 1830s in his manuscript, it's still not clearly clarified, especially the evolution of striation during gas breakdown.

In this paper, we study the evolution of striation in glow discharges through experiments driven by DC pulsed source and by Particle-In-Cell/Monte Carlo Collision (PIC/MCC) simulations. Then the formation of striations in DC glow discharge and in DBD will be compared.

2 Experimental setup and numerical modeling

2.1 Experimental setup

The discharge apparatus used in this work consists of a long cylindrical glass tube and a pair of aluminum disks, as shown in Fig. 1(a). The two metal electrodes are sealed with the glass tube, separated by a spacing of $L = 150$ mm. The inner diameter of the tube is $D = 10$ mm. The thickness and the relative permittivity of the glass are $e_r = 1$ mm and $\varepsilon_r = 6$, respectively. The tube is filled with pure argon at pressure of 40 Pa. A square-waveform voltage with rising time about 400 ns is applied on the anode. The cathode is grounded through a 24 kΩ sampling resistor $R$. The driving frequency is 1 kHz, which can ensure that each discharge is not affected significantly by the previous pulse. The voltage on anode and the discharge current are measured by digital oscilloscope (TektronixDPO4104) through voltage probes. An ICCD camera (Andor iStariDH734) was used to record the plasma images during the discharge developing. The optical

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shutter of the ICCD is synchronized by the trigger out signal of the oscilloscope. The gate width of the optical shutter is set to 100 ns.

### 2.2 PIC/MCC model

Since the discharge system is axis-symmetrical, the cylindrical coordinate is chosen and only half of the cross-section of the discharge apparatus is included in our simulation, as shown in Fig. 1(b) (highlighted by red dash line). The length $L$ and the diameter $D$ of the simulation region are equal to that of the discharge tube. The discharge process is analyzed by using PIC/MCC method [9]. To simplify the calculation, only two charged species (electron and Ar$^+$) are considered in this work. Since the magnetic field in the system can be neglected, electrostatic PIC model is used and the motion equation of the charged particles can be written as:

$$\frac{d}{dt} m_i \mathbf{v}_i = q_i E_i \quad (1)$$

where $m_i$ and $\mathbf{v}_i$ are the mass and the velocity of charged particles, respectively. The ionization ($\varepsilon_1 = 15.76$ eV), excitation ($\varepsilon_{ex} = 12$ eV) and elastic collision processes between electrons and Ar atoms are analyzed by MCC method. The cross sections of those collision processes are taken from Ref. [9]. The coefficients of secondary electron emission by Ar$^+$ impacting on aluminum and on the glass tube are 0.1 and 0.05, respectively.

![Fig. 1. Schematic diagram of discharge apparatus used in experiment (a) and in simulation (b).](image)

The electric field is described by Poisson's equation

$$\nabla \cdot (\varepsilon_0 \varepsilon_r \mathbf{E}) = \sum_i q_i n_i \quad (2)$$

where $\varepsilon_0$ and $\varepsilon_r$ are the vacuum permittivity and the relative permittivity of the glass tube, respectively. $\mathbf{E}$ is the electric field strength. $n_i$ represents the density of charged particle and $q_i$ its charge.

Dirichlet boundary condition is adopted at the anode and the cathode. At boundary of the glass layer, Neumann condition is used. The initial densities of electron and Ar$^+$ are both $10^{13} \text{ m}^{-3}$. The maximum number of macro-particle is $10^6$. The time step of Poisson solver is $10^{-11}$ s.

### 3 Results and discussion

#### 3.1 Formation of striations in pulsed glow discharge

In the experiment, the amplitude of the voltage pulse on the anode is 900 V. The frequency $f$ is 1 kHz and the duty ratio is 50%, viz. The width of the voltage pulse is 0.5 ms. Driving with the pulsed voltage, a stable striation of light radiation can be observed.

Fig. 2(a) shows the waveforms of the applied voltage and the discharge current in the gas breakdown phase. Fig. 2(b) is the images of the light radiation distribution in the glass tube at different moments after the rising edge of voltage pulse. Each image is obtained by integrating the light radiation with ICCD to improve the contrast. From the voltage waveform one can see that the voltage on the anode rose up to 1200 V in a short period (less than 0.2 $\mu$s). The voltage oscillated in 0.2-1.0 $\mu$s, then became stable at about 900 V in 2 $\mu$s. The current waveform shows that the discharge current was only about 0.5 mA in the voltage-rising phase, while in the stable discharge phase the current was about 5 mA. The ICCD image shows a luminous region formed at the region near the anode around 0.1 $\mu$s. It indicates that at the beginning of each pulsed discharge, intense excitation/ionization processes occurred near the anode firstly and a negative glow (NG) region was formed. This result also means that in our experiment, the striated distribution of light emission in the tube was not formed at the beginning of each discharge.

![Fig. 2. The experimental results with applied voltage 900 V at 1 kHz. (a) The waveform of voltage and discharge current, (b) The time-resolved image of light radiation.](image)
At about 2 μs, the current reached a peak of 6.5 mA. During this phase, the luminous region (the NG region) contracted toward the cathode, as shown by the result of 1.1 μs in Fig. 2(b). In this phase, striations had not yet to be observed between the negative glow and the anode. These experimental results indicate that the striation formation didn’t depend on the voltage oscillation at the pulse rising edge. At around 4.1 μs, the first striation was formed at the left side of the NG. At this moment, the Faraday dark space (between the first striation and the NG) and the positive column (from the first striation to the anode) could be distinguished clearly. As the current became stable, more striations emerged in the positive column one by one, as shown by the result of 9.1 μs.

The discharge process is also obtained by simulation. During the simulation, the anode is ground and the voltage on the cathode is set to a constant of ~1200 V, which corresponds to the initial status of each pulse. Fig. 3(a) shows the current on the cathode obtained in our simulation. The evolutions of the discharge and the striations are characterized by the spatio-temporal distribution of Ar⁺, as shown in Fig. 3(b).

![Fig. 3](image)

(a) The calculated current waveform and (b) the spatio-temporal distribution of Ar⁺ density

Similar to the discharge process observed in our experiment, there was a small current peak about 0.1 mA during 0.05-0.5 μs in the simulation. Initially, the density peak of Ar⁺ appeared near the anode, as shown in Fig. 3(b) at t=0.3 μs. As the current rose, the density peak of Ar⁺ would contract toward cathode, and negative glow appeared near cathode at 0.8 μs. This corresponds to the results of 0.1-1.1 μs in experiment. Thereafter, the first striation appeared when the NG moved towards the cathode further (t = 1.0 μs in Fig. 3(b)). After that more striations emerged in the positive column (t = 1.4 μs). Finally, the striations became stable in the tube as the discharge current decreased.

The simulation results are consistent with the experimental images of pulsed discharge. Firstly the NG region was formed in front of the cathode. Secondly, the first striation of Ar⁺ was formed in the positive column. Finally, more striations were formed one by one.

### 3.2 Striated distribution of potential

In order to analyze the relationship between the striations and the local potential, we provide in Fig. 4 the spatio-temporal distributions of the electrical potential in the tube. At the beginning, the electric field was uniform between the two electrodes. Electrons shifted toward the anode due to the effect of electrostatic force, and gained energy from the electric field to ionize and excite argon atoms. Due to the large mass, Ar⁺ will be accumulated in the space, as shown by the image of t = 0.3 μs in Fig. 4. As the positive space charges moved towards the cathode, a strong electric field would be formed near the cathode from z= 13.5 cm to 15 cm (t=0.8 μs in Fig. 4). This is the cathode fall (CF) region of glow discharge. The region from z= 12 cm to 13.5 cm was equipotential or field free, which corresponds to the NG region. Most ionizing and exciting processes occurred in the NG region to form a density peak of Ar⁺. The Faraday dark space (from z= 10 cm to 12 cm) separated the negative glow and the positive column. It is known that electrons will lose most of their energy at the end of the NG region. Electrons will gain enough energy from electric field to ionize/excite Ar atoms at the edge of the positive column. Thus the first striation was formed in the positive column around z = 9.5 cm, as shown by the image of t = 0.8 μs in Fig. 3(b). Comparing the distributions of potential and Ar⁺ at t = 0.8 μs in Fig. 4 and Fig. 3(b), it can be found that there was no striated potential in the area of the first striation before it has been formed. While at t = 1.0 μs, the striated potential (i.e. a potential well) appeared. From Fig. 4 at t = 1.0 μs, one can see that the distribution of potential in the first striation region was similar to that in the NG, except that the first striation appeared in the positive column with weak electric field.

At t = 1.0 μs, the electric field between the anode and the first striation was still uniform and weak. The potential distribution at t = 1.0 μs also shows that a potential well appeared in the region of the first striation. As the discharge developed, electrons would be conducted through the first striation region and move towards the anode. But the electrons with kinetic energy less than the potential well would be confined in the first striation. The kinetic energy of electrons escaping from the first striation region would become very low. For the weak axial field in the positive column, a certain distance along the axis was needed for electrons to reach the ionization/excitation energy of Ar.
atom. This would result in a new dark area, followed by another luminous region. Then a new striation was formed (Fig. 4, \(t = 1.4 \mu s\)). Finally, more stratified distributions of potential appeared in the positive column (Fig. 4, \(t = 2.6 \mu s\)). The simulation results indicate that pulsed glow discharge striations will gradually appear in a weak field channel.

![Fig.4 Potential distribution at different times](image)

### 3.3 Modulation effect of electric field on electron energy

The change of the electron energy when electrons pass through the striations exhibits a modulation effect of potential well on the electron energy. This effect can be demonstrated more clearly by the electron energy distribution function (EEDF). In order to analyze the change of electron energy, the first striation region (Fig. 3(b), \(t = 1.0 \mu s\)) is divided into two parts, i.e. the dark region DR and the bright region BR, as shown in Fig. 5. Then the EEDFs in DR and BR were calculated at \(t = 0.8 \mu s\) and \(t = 1.0 \mu s\), respectively.

![Fig.5 The dark region (DR) and the bright region (BR) used for EEDF calculation](image)

Fig. 6 shows the electron energy distribution functions. Before the striation was formed (Fig. 5, \(t = 0.8 \mu s\)), the peak of EEDF in DR was 2 eV and the averaged energy was 3.2 eV, as shown in Fig. 6(a). The percentage of electrons with energy above 12 eV (the excitation threshold of Ar atom) was only 1.23%. However, the peak of EEDF in BR was 5.5 eV and the averaged energy was 7.3 eV, which is much higher than that in DR. More energetic electrons led to strong exciting/ionizing processes in BR.

![Fig.6 EEDF in two regions (a) \(t = 0.8 \mu s\) before striation formation and (b) \(t = 1.0 \mu s\) after striation formation](image)

After the striation was formed (Fig. 5, \(t = 1.0 \mu s\)), the proportion of energetic electrons in bright region BR decreased significantly (see Fig. 6(b)). The potential difference in BR also was changed from 34 V to 2 V (Fig. 4). After passing through the BR region, the averaged kinetic energy of electrons would become lower. A dark region would be formed in the positive column. When electrons obtained enough energy from the weak field in the positive column, another striation would be formed. This is the modulation effect of the striation region on the electron energy, which causes more striations to form in the positive column.

### 3.4 Comparison with striations in DBD

Striations have also been found in dielectric barrier discharge (DBD) systems at variant pressures \([10-12]\). Generally, DBD operates in a pulsed discharge scheme. It is worth comparing the formation process of striations in DBDs with that in pulsed DC discharges.

Here we present a PIC/MCC simulation of DBD. The DBD structure consists of a pair of coplanar electrodes (X and Y) on one dielectric layer, and an assistant electrode A on the opposite dielectric layer \([13]\). Fig. 7 is the cross section diagram of the DBD cell. The distance between X and Y is 5 \(\mu m\). Then distance between two dielectric layers \(h = 1 \mu m\). The discharge gas is Ne+4\%Xe at 5 Torr. The discharge process during one pulse is studied. The potentials of \(-290\) V, \(190\) V, and \(0\) V are applied on the electrodes X, Y, and A respectively.
Fig. 7 The schematic diagram of DBD cell

Fig. 8 The spatial distribution of (a) Xe\(^+\) density, (b) the potential at different time

Fig. 8 shows the spatial distribution of Xe\(^+\) and potential during the discharge. At the beginning, electrons moved toward electrode A and, avalanche ionization occurred mainly in the region between X and A. A bunch of ions/excited Xe atom would be left in the space while electrons were accumulated on the dielectric layer below the electrode A, as shown in Fig. 8 at \(t = 14 \mu s\). A large equi-potential region (negative glow) was formed and contracted towards the electrode X as the discharge developing. At the same time, electrons would move along the dielectric layer under the electrode A by the effect of a weak transverse electric field. The first striation of Xe\(^+\) appeared in the weak field region near the dielectric layer (Fig. 8, \(t = 15.5 \mu s\)). The potential well was formed in the region of the first striation at \(t = 16.2 \mu s\) as electrons expanded further along the dielectric layer. The results in Fig. 8 show that the light emission striations were formed earlier than the potential well. The process of striations formation in DBD is similar to that in the pulsed discharge. The results confirm that the first striation in pulsed discharge plasma is formed by the modulated electrons coming from the NG region. As the modulated electrons moved towards anode, striations would be formed in a weak field plasma.

4 Conclusion

In this paper, the striation formation in pulsed discharge was studied by experiments and PIC/MCC simulations. The process of striation formation obtained by numerical simulation is consistent with the ICCD images in experiment. The change of electron energy distribution function before and after the striation formation shows clearly that electrons are modulated by the potential well of the space charges. The striations in pulsed glow discharge and DBD were compared. It can be confirmed that the mechanisms of striation forming are similar in both pulsed DC discharges and DBDs. The striations in a pulsed discharge appear gradually in the weak-field plasma, which indicates that the formation of striations in a pulsed discharge depends on the flow of the modulated electrons.

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