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Excimer emission from pulsed microhollow cathode discharges in xenon

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Direct current (dc) microhollow cathode discharge (MHCD) is an intense source for excimer radiation in vacuum ultraviolet at a wavelength of 172 nm in a high pressure xenon (Xe) gas. The concentration of precursors for the excimer formation, i.e., excited and ionized gas atoms, increases significantly by applying high voltage pulse onto the dc MHCD over the pulse duration range from 20 to 100 ns. The intensity of the excimer emission for the voltage pulse of 20 ns duration exceeds that of the emission intensity obtained from the same MHCD operated only in the dc mode, by one order of magnitude. In addition, the emission intensity increases by one order of magnitude over the pulse duration range from 20 to 100 ns. It can be assumed that the emission intensity of the MHCD source increases as long as the duration of the high voltage pulse is shorter than the electron relaxation time. For the high voltage pulse of 100 ns duration, the emission intensity has been found to be further enhanced by a factor of three when the gas pressure is increased from 200 to 800 mbar.

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I. INTRODUCTION

The microhollow cathode discharge (MHCD) generates a weakly ionized plasma between a hollow cathode with a circular hole of $\sim 100 \mu\text{m}$ and an arbitrarily shaped anode.^{1–7} The plasma is confined to the cathode hole in a pre-discharge mode at a relatively low current with a positive slope in the current-voltage characteristic. The plasma expands beyond the cathode hole by increasing the current in a glow discharge mode with a negative slope of the current-voltage characteristic. The expansion of the plasma with increasing current (at constant pressure) takes place as long as the discharge area is less than that of the electrode surface. After the plasma covers the whole electrode surface area, the current density increases with current, until finally an instability develops. This instability results in the constriction of the discharge and corresponds to glow-to-arc transition (GAT). Also, as the pressure is increased at constant current, the current density increases until reaching the threshold for the development of instabilities leading to GAT.

There are several methods to generate the excimer emission at high efficiency in the MHCD.^{2,5,6} One of the methods is to increase the discharge current through the MHCD. However, the onset of instabilities like GAT and thermal loading of the device limit the discharge current at the high pressure. The other method of increasing the discharge current without GAT or overloading the device includes the direct current (dc) discharge operation of the MHCD with a superimposed pulsed voltage. The application of the pulsed voltage onto the dc MHCD allows heating of the electrons without considerably increasing the gas temperature in the plasma as long as the duration of the voltage pulse is less than the critical time for the development of GAT.^{2,9} The high electric field due to the voltage pulse causes a shift of the electron energy distribution towards higher energies, which increases ionization and excitation rates. As a consequence,

the electron density increases through the enhanced ionization rate, and the precursors for the excimer increase through the enhanced excitation rate, which in turn is related to the excimer emission.

We have focused our experimental work on Xe rather than other gases because of its relatively high efficiency on the generation of the excimer emission.^{6–8} The precursors for the excimers, i.e., the atomic excited states of xenon (Xe), $^3\text{P}_1$ and $^3\text{P}_2$, are obtained from the impact of high energy electrons with Xe in ground state. These precursors create vibrationally excited excimer molecules, $\text{Xe}_2^*(^1\Sigma_u^+)$ and $\text{Xe}_2^*(^3\Sigma_u^+)$, via the three-body collision process. The first and second continuum radiations are obtained from the radiative decay of $\text{Xe}_2^*(^1\Sigma_u^+)$ and $\text{Xe}_2^*(^3\Sigma_u^+)$, respectively. The second continuum radiation with a peak at 172 nm dominates significantly at the high pressure above 100 mbar.⁵

The work described in this paper is concerned with the excimer emission behavior of the MHCD in Xe for its dc discharge operation with superimposed nanosecond and microsecond voltage pulses, i.e., pulsed dc mode operation. In this mode of operation, the response of the excimer emission intensity due to the pulsed voltage with pulse duration in the range of 20 ns to 1 μs is presented. A comparison between the pulsed dc mode and only the pulsed mode operation provides a simple method to determine the performance of the excimer emission in the MHCD. Further, the emission intensity has been compared for the gas pressure range of 200 to 800 mbar in the MHCD.

II. EXPERIMENTAL SETUP

A schematic experimental setup for the MHCD is shown in Fig. 1(a). The MHCD device comprises two parallel molybdenum electrodes separated by a mica insulator. The thickness of the electrodes and the insulator is 250 μm with a 200 μm diameter of their circular opening at the center. The

FIG. 1. (a) Schematic diagram of the experimental setup. (b) Self-matched transmission line pulse generator.

area of each electrode is 0.44 cm^2 and the capacitance of the MHCD device is 25 pF . A dc power supply (Heinzing, HNC 3500-40) is connected to the cathode electrode through a current limiting resistor, R_B , of $100 \text{ k}\Omega$ and the anode is grounded. The discharge voltage and current of the dc MHCD are measured by a high voltage probe (Tek P6015A) and a current viewing resistor of 100Ω , respectively. A high voltage pulse from a pulser is superimposed onto the dc discharge operation of the MHCD. A current probe monitor (Pearson 2877) is used to measure the current pulse in the MHCD.

The high voltage pulser is constructed using a self-matched transmission line technique powered by another dc supply (Fug HCN 140-6500) as shown in Fig. 1(b).¹⁰ For this pulser, an atmospheric pressure air spark gap is operated in a self-breakdown mode for fast switching. Such a transmission line pulser is used for generating a rectangular high voltage pulse. The duration of the rectangular pulse is equal to the transit time of the travelling wave through the transmission cable (RG 58 C) which is around 5 ns/m . Therefore, different pulse durations are obtained by changing the length of the transmission cable. The reflected pulse generated by mismatches at the load side travels through the cable and is absorbed by the matching impedance. The high voltage pulser for a relatively long pulse ($\geq 1 \mu\text{s}$) uses a single capacitor of $1.88 \mu\text{F}$ and a semiconductor switch, MOSFET (DE475-102N21A, IXYS), instead of the transmission cable and spark gap switch, respectively.

The optical emission is observed end-on from the anode side of the MHCD by a vacuum ultraviolet (VUV) monochromator (Acton Research 505) and recorded by means of a fast VUV photomultiplier tube (PMT, Valvo AVP 56 B) over a bandwidth of 5 nm and centered at 172 nm . A magnesium fluoride (MgF_2) lens window focuses the maximum anode hole area of the MHCD onto the entrance slit of the VUV monochromator.

III. MEASUREMENT RESULTS

A pulsed voltage of 1.5 kV from the spark gap assisted pulser across a resistive load of $1 \text{ k}\Omega$ is shown in Fig. 2. The rise time and pulse width of the output voltage are 6 and 20 ns , respectively. The pulse duration of 20 , 50 , and 100 ns corresponds to the transmission cable length of 4 , 10 , and

20 m , respectively. The applied voltage from the MOSFET based pulser is about 700 V . The rise time and pulse width of the output voltage from this pulser are 25 and 1000 ns , respectively. The spark gap switch has been used for the generation of short electrical pulses ($\leq 100 \text{ ns}$) because it has a higher switching speed than that of the MOSFET switch.

The sustaining voltage across the dc MHCD with a fixed current of 2 mA is dependent on the gas pressure. For example, the sustaining voltage decreases from 290 V at 400 mbar to 220 V at 800 mbar . A drop in the sustaining voltage with the increased pressure is related to the increased ionization in the discharge. Fig. 3 shows the temporal development of the discharge voltage and current due to the superimposed high voltage pulse of $1 \mu\text{s}$ duration on the dc MHCD in Xe at 800 mbar . Voltage reversal is obtained due to the decrease in the discharge impedance over the time of the pulse. The discharge voltage with the rise time (10%–90%) of 30 ns has its peak at -700 V . The discharge current rises for 130 ns before it reaches a steady state value of 26 A . The peak of the discharge voltage lasts for 20 ns and then decays within 300 ns to the lower voltage of -50 V for the rest of the steady state current pulse. The discharge voltage experiences a reverse polarity of 50 V during the falling edge of the current pulse. The pulse duration at FWHM of the steady state current is almost equivalent to that of the applied voltage.

FIG. 2. Waveform of a 20 ns pulse generated by the transmission line pulse generator. The voltage is measured across a $1 \text{ k}\Omega$ load.

FIG. 3. Temporal development of discharge voltage, discharge current and VUV emission intensity from the MHCD in 800 mbar xenon when a $1\ \mu\text{s}$ voltage pulse is applied to the dc discharge.

Fig. 4 shows the temporal development of the discharge voltage and current of the MHCD in response to the applied pulsed voltage with a pulse duration in the range of 20 to 100 ns. The pulsed voltage with a peak at 1.5 kV is superimposed on the dc MHCD in Xe at 800 mbar. Voltage reversal similar to that of the $1\ \mu\text{s}$ pulse duration is again obtained due to the decrease of the discharge impedance over the time of the pulse duration. The discharge voltage with the rise time of 6 ns has its peak at 1.5 kV. The peak voltage remains for 20 ns which is independent of the pulse duration and then decays gradually. The peak voltage in the reverse polarity is 1 kV during the falling edge of the current pulse. It is to be noted that the discharge voltage of the MHCD drops to zero in both cases, for the short and long current pulses, when the applied voltage pulse stops and then returns to the dc voltage after several microseconds.⁴ The discharge current increases from 18 to 36 A with increasing pulse duration of 20 to 100 ns, respectively. A similar dependence of the discharge voltage and current on the MHCD is obtained over the pressure range of 200 to 800 mbar. Fig. 4 further indicates that the rise time of the discharge current increases with increasing voltage pulse duration. For example, the current rises

FIG. 4. Temporal development of discharge voltage and current in the MHCD for 800 mbar xenon pressure at different high voltage pulses.

rapidly ($\sim 30\ \text{ns}$) up to 25 A in the case of the 100 ns voltage pulse and reaches a current level of 36 A after an additional 60 ns, approaching a steady state. While in the case of 20 ns voltage pulse, the current reaches its peak in 20 ns without entering into a steady state.

The temporal development of the excimer emission intensity in the VUV wavelength in response to the pulsed dc operation is shown in Fig. 5. It corresponds to the previous Fig. 4 for three different high voltage pulse durations. The emission intensity in the dc operation is constant with a relatively low intensity, which is less than 10% of the maximum intensity with the voltage pulse of 20 ns duration. The peak emission intensity of 0.5, 3.3, and 6.3 a.u. (arbitrary units) corresponds to the applied high voltage pulse duration of 20, 50, and 100 ns, respectively. The rise time of the emission intensity increases with increasing pulse duration similar to that of the current pulses. For example, the rise time of the peak emission intensity is 15, 30, and 60 ns for the applied pulsed voltage duration of 20, 50, and 100 ns, respectively. It is evident that the peak emission intensity with the pulsed voltage of 100 ns duration is an order of magnitude higher than with the pulsed voltage of 20 ns duration.

The VUV emission intensity reaches its peak value simultaneously with the peak current and then it decays to its dc value on a time scale exceeding the duration of the applied voltage pulse by a factor of six. The duration of the emission intensity at FWHM is similar to the duration of the current pulse. In fact, the time to reach the peak of the emission intensity increases with the increase of the pulse duration up to 100 ns. However, the peak intensity does not increase with a further increase of the pulse duration as shown in Fig. 3 for the applied voltage pulse of $1\ \mu\text{s}$ duration. Here, FWHM of the peak emission intensity is much shorter than the duration of the current pulse. The emission intensity decays to half of its peak value and its dc value after 0.5 and $1\ \mu\text{s}$, respectively. It is to be noted that such steps increase with increasing voltage pulse duration. A possible reason for the decay of the emission intensity is the dissipation of the electron energy in the plasma in a time scale corresponding to the energy relaxation time which is much shorter than that of $1\ \mu\text{s}$ voltage pulse.

FIG. 5. Temporal development of VUV emission intensity from the MHCD in 800 mbar xenon at different high voltage pulses.

The emission intensity of the VUV radiation increases significantly, depending on Xe pressure, in the pulsed dc operation compared with that using only the pulsed voltage operation. For example, the emission intensity from the MHCD in the pulsed dc operation with the pulse duration of 100 ns at 400 mbar of Xe pressure is slightly higher than that using only the pulsed voltage of similar duration as shown in Fig. 6. The VUV emission intensity remains the same in the pressure range of 400 to 800 mbar for only the pulsed voltage operation while it increases by a factor of three over the same pressure range when the operation of the dc microplasma in the MHCD is superimposed by the pulsed voltage. The increase of the emission intensity is due to the pulse electron heating that shifts the electron energy distribution to higher values.^{2,5} The shift in the electron energy distribution towards higher energies causes an increase in the ionization rate, and consequently a strong rise in the electron density at high pressure with energies larger than the excitation energy of the gas atoms. Hence, the operation of the dc MHCD with superimposed pulsed voltage favors excimer formation at relatively high pressure, making it an efficient excimer source. For example, the VUV emission intensity in the pulsed dc operation increases over the gas pressure range from 200 to 800 mbar for the voltage pulse of 100 ns duration as shown in Fig. 7. A similar response of the emission intensity has been obtained over the same pressure range for the voltage pulse of 20 and 50 ns durations.

The electrical energy is calculated by integrating the product of the discharge voltage and current for 1 μ s duration from the application of the voltage pulse. In our experiment, the temporal behavior of the discharge voltage and current remains the same over the pressure range from 200 to 800 mbar. Therefore, the electrical energy is nearly the same at all pressures but increases with the increasing voltage pulse duration. The electrical energy with the voltage pulse of 50 ns duration is almost three times that of the voltage pulse of 20 ns duration. However, the electrical energy is not even doubled when the voltage pulse is increased from 50 to 100 ns. The peak voltage appears only within 20 ns across

FIG. 6. Comparison of VUV emission intensity for the case that a 100 ns pulse was superimposed on the dc voltage, and for the case that the discharge was generated by applying a 100 ns pulse only.

FIG. 7. Temporal development of VUV emission intensity for the high voltage pulse of 100 ns duration at different Xe pressures.

the MHCD regardless of the applied voltage pulse duration. However, the peak value and FWHM of the current pulse increases significantly for the voltage pulse when increased from 20 to 50 ns, and less significantly for the voltage pulse when increased from 50 to 100 ns.

The total VUV intensity is obtained by integrating the emission intensity over its time duration. The VUV emission efficiency is then defined as the ratio of the total VUV intensity over the electrical energy. The emission efficiency of the MHCD increases with increased Xe pressure and pulse duration as shown in Fig. 8. The emission efficiency increases significantly with increasing pressure for the voltage pulse of 100 ns duration compared to that for the voltage pulse of 20 ns duration. It also illustrates that there is no steady state behavior in the emission efficiency for the pulse duration and pressure regime investigated.

IV. DISCUSSION

The discharge voltage and current characteristics have been investigated by superimposing high voltage short

FIG. 8. VUV emission efficiency of the MHCD at different pressures and pulse durations.

electrical pulses onto the dc MHCD for its excimer source and is presented in Figs. 4 and 5. The electron energy distribution in the microplasma is, due to the superimposed pulsed electric field, shifted towards higher energies. The high energy electrons due to increased excitation and ionization rates provide a high concentration of excimer precursors. In addition, the high pressure operation, which favors excimer formation, makes the pulsed MHCDs very efficient excimer radiation emitters. Because of the short pulse duration, thermal effects are minimized. The excimer emission intensity of the MHCD for the pulsed dc operation is higher than that of the emission intensity obtained from either only the dc MHCD or the pulsed MHCD as shown in Figs. 5 and 6. The emission intensity increases by a factor of three over the pressure range from 200 to 800 mbar as shown in Fig. 7. In addition, the emission intensity increases with increasing voltage pulse duration from 20 to 100 ns as shown in Fig. 5 at 800 mbar of Xe pressure. In fact, the peak emission intensity for the voltage pulse of 100 ns duration is about an order of magnitude higher than the voltage pulse of 20 ns duration. As a consequence, the efficiency of the excimer emission increases with both pressure and pulsed voltage duration.

The VUV emission is then limited by the relaxation time upon a further increase of the pulse duration beyond 100 ns. The electrons transfer their energy to the atoms via collisions in a time corresponding to the energy relaxation time which is 124 ns for Xe gas at 800 mbar.¹¹ This causes heating of the gas that destroys the precursors for the excimer formation. For example, the emission intensity reaches the steady state and then decays within 300 ns after the application of the voltage pulse as shown in Fig. 3. On the other hand, if the applied voltage pulse is increased to a sufficiently high value, the current also increases and the MHCD due to the high power density is prone to radial constriction of discharge column and formation of GAT. It means the high current could be generated by extending the discharge plasma on the cathode surface for a short time rather than by the discharge plasma inside the hole of the MHCD. In fact, the applied voltage pulse must be adjusted with pressure because the higher the pressure the higher the breakdown voltage required. However, there should be a restriction on the voltage pulse duration because the higher the applied voltage, the shorter the pulse duration needs to be. In this manner, excessive heating of the gas can be avoided.

V. CONCLUSION

The electrical characteristics and the emission of the excimer radiation from the dc MHCD in Xe gas were investigated, where short electrical pulses were superimposed on the dc discharge voltage. The pulse electron heating of the glow discharge in the dc MHCD, with minimal influence on the gas heating, increased the emission intensity of VUV radiation at 172 nm. By applying the high voltage pulse of 20 to 100 ns durations to microplasmas, generated by the dc MHCD, we were able to increase the excimer emission intensity by more than one order of magnitude compared to the dc mode itself and by a factor of three compared to the pulsed mode only. Since the favorable condition for the three-body process in the excimer formation increases with pressure, we were able to increase the excimer emission in the MHCD in the pressure range of 200 to 800 mbar. The pulsed dc operation of the microplasma in the MHCD can be extended to the operation of tandem MHCDs (several MHCD in series) or capillary discharges in series for the generation of intense VUV radiation.^{6,11}

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