Xenon excimer emission from pulsed high-pressure capillary microdischarges

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Intense xenon vacuum ultraviolet (VUV) emission is observed from a high-pressure capillary cathode microdischarge in direct current operation, by superimposing a high-voltage pulse of 50 ns duration. Under stagnant gas conditions, the total VUV light intensity increases linearly with pressure from 400 to 1013 mbar for a fixed voltage pulse. At fixed pressure, however, the VUV light intensity increases superlinearly with voltage pulse height ranging from 08 to 2.8 kV. Gains in emission intensity are obtained by inducing gas flow through the capillary cathode, presumably because of excimer dimer survival due to gas cooling. © *2007 American Institute of Physics*.
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Several topical reviews in recent years emphasized the scientific interest and the important applications of microdischarges operated in the hollow cathode mode.[1–3] These microdischarges form stably at high pressures (1 atm or higher) through the presence of a sufficient concentration of high-energy electrons undergoing a Pendel oscillation. Operation under these conditions (high pressure, high-energy electrons) favors the formation of excimer dimers, which renders these microdicharges useful as sources of intense vacuum ultraviolet (VUV) emission from rare gases[4–7] and UV emission from rare gas halides.[8,9] However, most of the reported experiments were performed in direct current (dc) microdischarges, where gas heating can destroy excimer dimers thus limiting the radiant power of the VUV emission. Thermal heating can be reduced by pulsing the discharge. Recently, an increase in the radiant power of xenon[10] and argon[11] excimer emission, from planar dc microdischarges was observed after a high-voltage pulse (sub-kilovolts 20 ns) was superimposed. However, the enhancement was attributed to the increase in the plasma area over the cathode surface resulting from high voltage and current. This effect is incompatible with an excimer microlaser, which requires an on-axis increase in plasma volume.[7]

In this letter, we report enhanced VUV emission from the application of a high-voltage (>1 kV) pulse to a dc capillary microdischarge. The enhancement is believed to originate from the increase in on-axis plasma volume in the metallic capillary cathode. Applying a high-voltage pulse to the capillary microdischarge may result in current densities above the threshold for the glow-to-arc transition (GAT). This condition was avoided by selecting the pulse duration to be shorter than the time constant of the dominant instability that causes the GAT transition.[12] For improved VUV characteristics, it is critically important to avoid emission caused by secondary current pulses as the pulsed voltage relaxes to zero.[13] The latter effect was avoided by using a self-matched transmission line pulsen generator,[14] consisting of a 10-m-long 50 Ω coaxial cable, which fixed the pulse duration to 50 ns. The matching impedance minimized the reflection of the current pulse that arises from the time-variable impedance of the gas discharge. A fast rise time of the pulsed voltage was obtained by using a spark gap.

The experimental setup for the pulsed capillary discharge is shown in Fig. 1. The cathode consists of a stainless steel capillary tube with inside diameter of 180 μm and a length of 5 mm. A stainless steel mesh served as the anode. A 250-μm-thick mica sheet with a centered hole of 200 μm prevented the plasma from expanding on the cathode outer surface. The microdischarge was generated by two dc power supplies, one for establishing a cw microdischarge and the other for providing the 50 ns voltage pulses through the self-matched transmission line. Experiments were conducted in pure Xe with and without forced gas flow through the microdischarge.

Figure 2 shows the time resolved measurement of the electrical characteristics for the pulsed capillary microdischarge in a pressure of 1013 mbar. Initially, the dc microdischarge was formed at a sustaining voltage of 200 V with a current of 3 mA. Then, a 1.5 kV pulse with a rise time (10–90%) of 7 ns was superimposed for 50 ns [full width at half maximum (FWHM)] to this dc discharge. The voltage across the discharge was measured by a voltage probe (Tektronix P5100) and the current was measured by a current monitor (Pearson 2877). The voltage pulse coincides with an abrupt increase in discharge current of equal duration. The peak

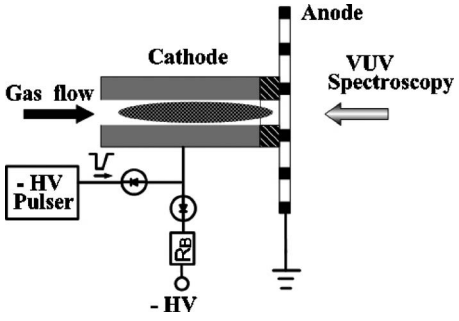

FIG. 1. Schematic diagram of the experimental setup.

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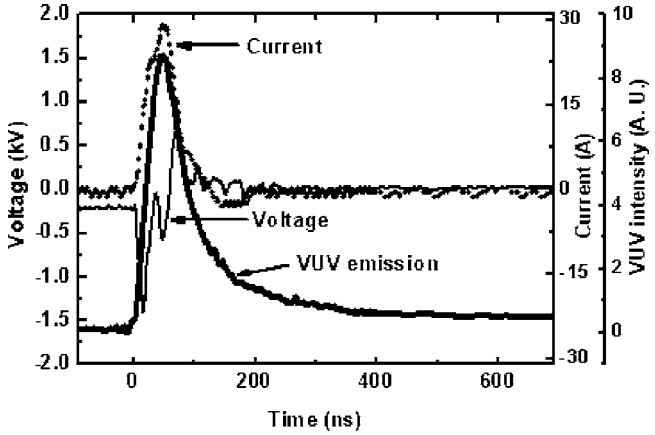

FIG. 2. Temporal development of the discharge current, voltage, and the VUV emission at 172 nm.

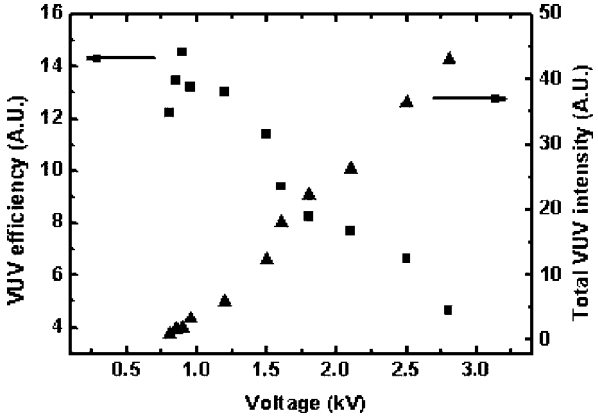

FIG. 4. VUV efficiency and total VUV intensity for the different amplitudes of voltage pulses.

current value was approximately 28 A. During the decay of the voltage pulse, the discharge voltage drops to zero but recovers to its dc value (200 V) after 20 μs. The temporal development of the Xe excimer emission at 172 nm during pulsing is also shown in Fig. 2. The emission was collected through the mesh anode and was focused on the entrance slit of the VUV monochromator (Acton Research VM 505, 1200 G/mm grating blazed at 190 nm) using a magnesium fluoride (MgF_2) lens. The temporal development of the VUV emission was detected by means of a fast VUV photomultiplier (Valvo AVP 56 B) integrating over a bandwidth of 5 nm centered at 172 nm. The internal delay time of the photomultiplier was compensated with respect to the voltage signal and the current signal. Very low intensity of the VUV emission was observed during dc operation, consistent with the low discharge current. However, when the high-voltage pulse was applied, the emission intensity increased rapidly in step with the discharge current, reaching a value almost two orders of magnitude larger than that for the dc operation. Although the peak VUV intensity coincides with the discharge current maximum, the emission decays exponentially to its dc value with a time scale one order of the magnitude longer than the duration of the applied voltage pulse.

The temporal behavior of the VUV emission was also investigated as a function of the pressure from 400 to 1013 mbar (see Fig. 3). In this pressure range, the VUV intensity during dc operation is small and changes very little. Superposition of the pulsed voltage caused the peak VUV intensity to increase roughly proportional to the pressure. For instance, the peak VUV intensity at 1013 mbar was about 2.5 times larger than that at 400 mbar. No time delay for the appearance of the VUV emission pulses was observed with increasing pressure. The width (FWHM) of the VUV emission pulse was about 70 ns regardless of pressure. The exponential decay of the VUV emission occurred slightly faster at the higher pressures. This suggests an increased collisional rate for the Xe^* conversion into Xe_2^*, that is, an increased collisional quenching effect.[11] The decay of the second continuum Xe_2^* results from the loss rate of the Xe^* ($^1S_5$).[15] The total VUV intensity, obtained by integrating the VUV emission wave forms, increased linearly with the gas pressure (not shown).

The VUV emission intensity also depends on the magnitude of the applied voltage pulse. Figure 4 illustrates the variation in total integrated intensity when the applied voltage pulse height is raised from 0.8 to 2.8 kV at 1013 mbar. The observed superlinear dependence is attributed to nonequilibrium effects in the pulsed discharge.[10] The VUV emission efficiency, defined as the ratio of the total VUV intensity over the electrically consumed energy, first increased slightly with pulsed voltage up to 0.9 kV, but then it decreased linearly with pulsed voltage. Thus, to increase VUV emission,

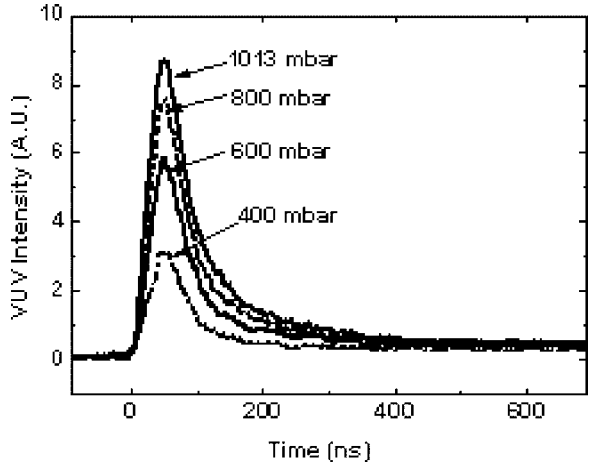

FIG. 3. Temporal development of the VUV emission for the different pressures (400–1013 mbar).

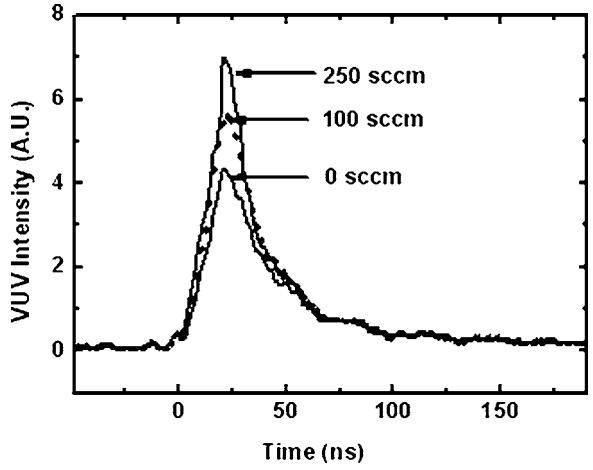

FIG. 5. Temporal development of the VUV emission for different gas flow rates.

a disproportionately larger power must be delivered to the microdischarge.

The influence of forced gas flow through the capillary cathode on VUV emission was also investigated for pulsed discharge operation. Figure 5 shows the temporal evolution of the VUV emission as a function of the flow rate of ambient Xe through the capillary tube. The gas flow rate was controlled by means of a flow meter, while maintaining an ambient pressure of 1013 mbar. For this particular experiment, the applied voltage on the VUV photomultiplier was reduced in order to avoid any possible saturation in the measurement. When the pulsed voltage was applied to the microdischarge under forced flow, the temporal evolution of the VUV emission exhibited differences from that observed in the stagnant gas (see Fig. 3). The peak VUV intensity improved with flow rate, possibly due to increased neutral gas density and reduced decomposition of the excimer dimers as a result of the cooling effect of the gas flow. The improvement in VUV emission with gas flow for pulsed microdischarge operation is very small when compared with that reported for dc operation at much higher discharge currents, where heating effects are a lot more substantial.[7]

In conclusion, superimposing a high-voltage pulse on a dc capillary cathode microdischarge operated in Xe gas ambient permits substantial gains in VUV emission intensity, especially with increasing voltage pulse height, operating pressure, and forced flow rate through the microdischarge. Thus, pulsed operation may increase the chances of constructing an excimer microlaser using stacked capillary cathode microdischarges to provide sufficient active gain length.[7]

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