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## Comparison between the ultraviolet emission from pulsed microhollow cathode discharges in xenon and argon

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We measured the dynamic  $I-V$  characteristics and vacuum ultraviolet (VUV) emission lines of the second continuum in xenon (170 nm) and argon (130.5 nm) from pulsed microhollow cathode discharges (MHCD). For pulse lengths between 1 and 100  $\mu\text{s}$  the dynamic  $I-V$  characteristics are similar in both inert gases. Only the time variation of the VUV emission line at 170 nm for xenon can be related to the dimer excited states. In argon the energy transfer between the  $\text{Ar}_2^*$  dimers and the oxygen impurity atoms is responsible for a qualitatively different time behavior of the resonance line at 130.5 nm. Consequently, the relative VUV efficiency reveals an inverse dependence on the electrical pulse lengths for the MHCD in xenon and argon, respectively. © 2003 American Institute of Physics. [DOI: 10.1063/1.1626020]

The excimer emission of various high-pressure discharges in rare gases and rare gas halides has been found to be an efficient noncoherent radiation source in the ultraviolet range. Therefore, the excimer emission of the microhollow cathode discharges (MHCD)<sup>1-4</sup> have been systematically investigated due to its low operating voltage and simple geometry which allows the fabrication of arrays<sup>5-7</sup> or serial multistage devices<sup>8-10</sup> even with plane cathodes.<sup>8</sup> It has long been recognized that, besides the discharge geometry and gas pressure, the vacuum ultraviolet (VUV) intensities increase with the discharge current.<sup>1</sup> But, to avoid a thermal overload of the MHCD devices a further increase of the discharge power can be achieved only for the pulsed operation. Up to now, little information was available for the pulsed operation of MHCD in xenon<sup>4</sup> with very long voltage pulses of several 100  $\mu\text{s}$ . Only recently,<sup>2</sup> data have been reported for the VUV emission of pulsed MHCD in xenon but for very short voltage pulses of only 20 ns.

In this letter we present some results obtained for the  $I-V$  characteristics and VUV emission in xenon and argon from standard<sup>11</sup> MHCD devices, i.e., with the planar geometry used by Schoenbach,<sup>1,2</sup> operated with short voltage pulses from 1 to 100  $\mu\text{s}$  and repetition rates of 10 and 100 Hz. The temporal behavior of the  $I-V$  characteristics and the VUV emission for the pulsed mode of operation will be presented and discussed. Then, the influence of the pulse length on the relative VUV efficiency, defined by the ratio between the relative VUV radiation output and the input of electrical power, will be given.

The MHCD device consists of 100- $\mu\text{m}$ -thick molybdenum electrodes separated by a 250- $\mu\text{m}$ -thick alumina insulator. The discharge channel of 100  $\mu\text{m}$  diameter through both the electrodes was drilled by laser ablation. A magnesium

fluoride lens separates the high-pressure MHCD chamber from the Acton Research monochromator with a grating of 1200 G/mm blazed at 150 nm. The same lens images, end-on, the whole microdischarge from the cathode side onto the entrance slit of the monochromator. An Acton Research VUV-photomultiplier whose signal was processed by a digital Tektronix has been used to record the diffracted light.

Figures 1 and 2 show the typical wave forms of discharge voltage and current together with the temporal behavior of VUV emission intensity in xenon and argon for two different pulse lengths of 5 (or 10  $\mu\text{s}$ ) and 100  $\mu\text{s}$ , respectively. The VUV emission has been integrated over a bandwidth of 5 nm centered at 170 nm wavelength for xenon and at 130.5 nm for argon. Apart from the different breakdown

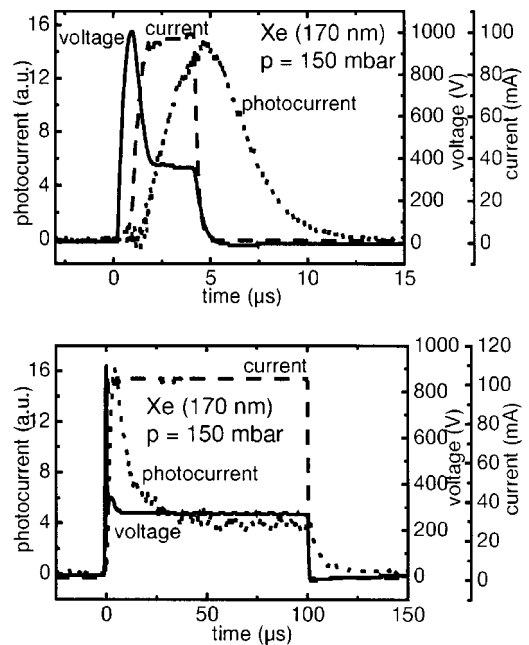


FIG. 1. Typical time development of the discharge voltage, current, and the vacuum ultraviolet emission at 170 nm of the pulsed MHCD at a xenon pressure of 150 mbar. The two electrical pulse lengths are 5 and 100  $\mu\text{s}$ , respectively. The pulse repetition rate was 10 Hz.

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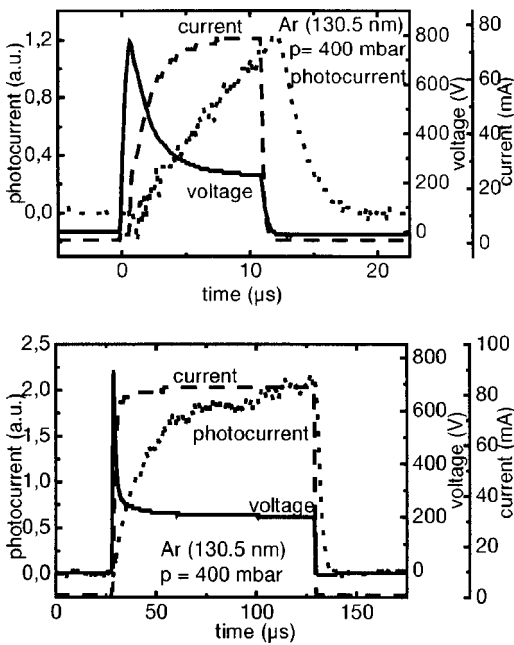
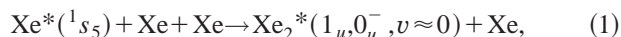


FIG. 2. Typical time development of the discharge voltage, current, and the vacuum ultraviolet emission at 130.5 nm of the pulsed MHCD at an argon pressure of 400 mbar. The electrical pulse lengths are 10 and 100  $\mu\text{s}$  length, respectively. The pulse repetition rate was 100 Hz.

and dc operation voltage, the transient behavior of the electrical characteristics remains almost the same for both gases. However, the time dependencies of the VUV emission are qualitatively different. It is seen in Fig. 1(a) that the xenon VUV emission increases relatively slowly reaching its maximum at about 3  $\mu\text{s}$  after the current increase. For shorter voltage pulses this VUV radiation peak occurs even after the termination of the current pulse, a behavior which was also observed elsewhere.<sup>2</sup> However, this peak of the VUV emission in xenon is still different from the true afterglow observed recently for a MHCD in neon.<sup>12</sup> After reaching the peak, the emission from the second continuum in xenon decreases with a time constant of somewhat larger than 7  $\mu\text{s}$ . Both time constants, for the increase and decay of the VUV emission at 170 nm in xenon, are nearly independent on the voltage pulse lengths. These data agree very well with the time constants measured for a surface type ac plasma display panel cell<sup>13,14</sup> in xenon and mixtures of Xe–He (Ne). In Ref. 14, for example, the typical reactions for the emission of the second continuum were simplified to one reaction



where the xenon dimers are generated from  $\text{Xe}^*(^1s_5)$  and decay by emitting second continuum radiation. Because the generation takes more time than the radiative de-excitation and the radiation decay is determined by the slow process, the decay of the second continuum reflects the loss rate of  $\text{Xe}^*(^1s_5)$ , thus establishing the time variation of VUV emission at 170 nm.

Returning to our measurements, it is shown in Fig. 1(b) that a stationary (or slowly decaying) state of the VUV emission at 170 nm with a relative intensity of only 25% from its peak value is reached at 25  $\mu\text{s}$  after the current increase. Consequently, by decreasing the pulse lengths, the slowly decaying radiation is eliminated whereas the VUV radiation

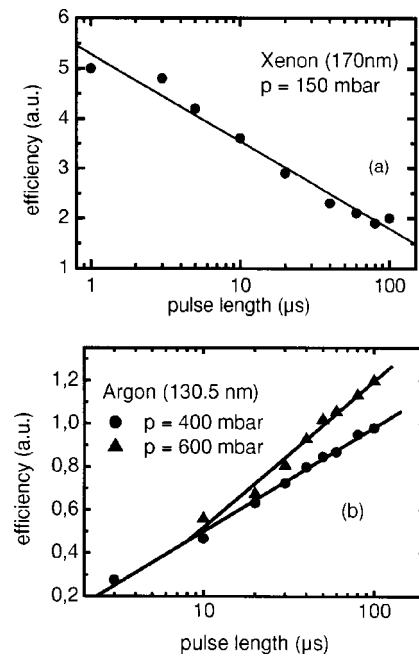


FIG. 3. The electrical efficiency for the VUV emission of the pulsed MHCD as a function of the pulse duration: (a) at 170 nm for the xenon pressure of 150 mbar and (b) at 130.5 nm in argon for the pressures of (●) 400 and (▲) 600 mbar. The pulse repetition rates are the same as in Figs. 1 and 2, respectively.

peak remains nearly constant even for pulse lengths shorter than a few microseconds. Therefore, this overall transient behavior of the VUV excimer radiation in xenon explains the corresponding higher relative VUV efficiency obtained for shorter pulse lengths, as shown in Fig. 3(a). As known,<sup>2</sup> this relative VUV efficiency can be much higher for very short voltage pulses of a few 10 ns. For pulses, long compared to 25  $\mu\text{s}$  this efficiency approaches that of dc operation.

A qualitatively different time development of a VUV emission line has been recorded for argon at the wavelength of 130.5 nm with a bandwidth of 5 nm. As shown in Fig. 2 the VUV intensity increases slowly over the whole pulse length, reaching saturation at about 100  $\mu\text{s}$  after the current rise. This result indicates that the VUV emission for shorter voltage pulses corresponds to the initial part of the emission observed with long pulses, with the corresponding decrease of the VUV radiation output and relative VUV efficiency. Recent studies<sup>15</sup> have been shown that, rather than the argon dimer continuum, the emission of the O I resonance lines around 130.5 nm dominates the VUV spectrum in this wavelength range. It was shown that these lines can be easily observed even with only trace amounts (<1%) of oxygen in argon. This was explained by a nearly resonant energy pumping from the  $\text{Ar}_2^*$  dimer state to the atomic oxygen transitions. A similar behavior was found for the excimer formation in helium, where the narrow emission lines of O, N, and H atoms as impurities were observed.<sup>16</sup> This can explain the increase of the VUV relative efficiency with pulse length in argon, as shown in Fig. 3(b). The impurities cause the reduction of excimer formation since the presence of impurities reduces the generation of excited states. Another effect of the oxygen impurities is the collisional quenching of the excited argon atoms, the precursor of the excimers. Possible sources of the oxygen impurities are small leaks in the

MHCD chamber, water vapor remnants, or even emissions from the dielectric layer ( $\text{Al}_2\text{O}_3$ ) due to high gas temperature. By flowing the argon gas, it was recently shown<sup>17</sup> that the impurity lines almost disappeared, and the excimer continuum intensity substantially increased. By superimposing a 800 V, 10 ns voltage pulse to a dc operating MHCD in this flowing argon a very fast increase and an exponentially decaying argon excimer emission with a time constant of about  $0.5 \mu\text{s}$  was recorded. But, since the argon excimer lifetime lies between 3 and  $4 \mu\text{s}$ ,<sup>18</sup> the observed fast decay implies that the temporal decrease in excimer emission is not only due to radiative decay but that other processes such as collisional quenching are involved. The rate equation for excimer decay can be written as<sup>17</sup>

$$d[\text{Ar}_2^*]/dt = -[\text{Ar}_2^*](A_{ik} + 1/k_q[q]), \quad (2)$$

where  $[\text{Ar}_2^*]$  is the argon excimer density,  $A_{ik}$  is the inverse spontaneous lifetime of the argon excimers, and  $k_q[q]$  is the sum of all quenching rates. According to Eq. (2) and an exponentially decaying intensity, the total decay time constant,  $\tau$ , is given by

$$1/\tau = A_{ik} + 1/k_q[q], \quad (3)$$

and so the time constant of the quenching processes would be  $0.56 \mu\text{s}$ . Therefore, quenching is six times more effective than radiative decay. By varying the voltage pulse from 600 to 800 V it was shown<sup>17</sup> that the quenching time constant can change between 0.5 and  $1.6 \mu\text{s}$ . Consequently, with decreasing pulsed voltage, collisional quenching seems to become less important, and the decay is determined by radiative processes.

Theoretical studies<sup>11</sup> on the transition between the conventional hollow cathode discharge (HCD) and the so-called standard MHCD for a constant value of  $pR = 1$  Torr cm have shown, that the power per unit volume, degree of ionization, the excitation and ionization rates, and the electron density increase as a cube or square of the neutral gas pressure, respectively. Consequently, the conventional HCD with hole diameters of a few centimeters and the MHCDs with submillimeter dimensions have very different properties, except for

the current–voltage characteristics which are practically the same for both discharges. Indeed, our data prove that for the plasma of MHCD in rare gases the temporal development of the VUV emission after pulsed current application is determined by complex gaseous electronics processes rather than simply by the temporal development and the amplitude of the discharge current.

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