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Xenon excimer emission from pulsed microhollow cathode discharges

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By applying electrical pulses of 20 ns duration to xenon microplasmas, generated by direct current microhollow cathode discharges, we were able to increase the xenon excimer emission by more than an order of magnitude over direct current discharge excimer emission. For pulsed voltages in excess of 500 V, the optical power at 172 nm was found to increase exponentially with voltage. Largest values obtained were 2.75 W of vacuum-ultraviolet optical power emitted from a single microhollow cathode discharge in 400 Torr xenon with a 750 V pulse applied to a discharge. Highest radiative emittance was 15.2 W/cm^2. The efficiency for excimer emission was found to increase linearly with pulsed voltages above 500 V reaching values of 20% at 750 V. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1397760]

Excimers are weakly bound excited states of molecules which decay radiatively emitting quasimonochromatic ultraviolet and vacuum-ultraviolet (VUV) radiation. They are formed in high-pressure rare gases and rare gas halides in self-sustained or externally sustained plasmas. Excimer lamps have found a variety of applications, including lighting, surface processing, material deposition, and bacterial decontamination.[1] Although most of the excimer lamps are based on barrier discharges, other types of excimer lamps, including microwave excited lamps,[2] and microhollow cathode discharge lamps[3] are gaining attention as alternative VUV sources.

Microhollow cathode discharges are direct current, high-pressure gas discharges between perforated electrodes, separated by thin layers of dielectric material.[4] The thickness of the electrodes and the dielectric layers is in the range of 100 μm, while the hole diameter varies between 100–200 μm. The electrons emitted from the circular cathode and accelerated in the cathode fall gain sufficient energy to excite rare gas atoms. Experiments in xenon,[5] argon,[6] neon,[7] and helium[8] have been performed, and excimer emission has been obtained in any of the rare gases, with highest efficiencies of 6% to 9% in xenon.[9] Excimer emission in rare gas halide discharges (ArF and XeCl) was found to have efficiencies in the range of up to 3%.[3] Whereas the efficiency in xenon, the most thoroughly studied excimer gas showed a maximum at approximately 400 Torr, the radiative emittance increases monotonically with pressure up to values of 2 W/cm^2 at pressures of 760 Torr. The discharge current only affects the value of the optical power—a linear increase in excimer emission was found with increasing current up to 70 mA—but not the efficiency.[10]

The theoretical value of the efficiency for excimer emission in cold plasmas is much higher than the measured one for microhollow cathode discharges: 40% according to Ref. 11, 60% according to Ref. 12. The relatively low value obtained in dc microhollow cathode discharges is assumed to be due to gas heating (estimates of the power dissipation in the cathode plasma indicated values exceeding 100 kW/cm^3) and/or due to contamination of the excimer gas by sputtered and evaporated electrode material. Both effects cause increased depopulation of excited atomic states, the precursors of dimers.

A method to increase the excimer efficiency in glow discharges is pulsed electron heating. Experiments in atmospheric pressure air[13] had indicated that extremely short pulses can affect the electron kinetics without heating the plasma. The pulsed electric field shifts the electron energy distribution to higher values and consequently causes a nonlinear increase in the excitation and ionization rates. This pulsed electron heating effect might also be—at least in part—responsible for the observed increase in the efficiency in barrier discharge excimer lamps,[14] where increases in efficiency by a factor of 3.2 were obtained.

Whereas for pulsed barrier discharges kV pulses need to be applied, pulsing microhollow cathode discharges into the nonequilibrium condition can be achieved with sub-kV pulsed voltages. We have used a metal–oxide–semiconductor field effect transistor as switch in a Blumlein line type pulser[15] to generate pulses with 10 ns risetime and pulse duration of 20 ns, with peak voltages up to 750 V. The pulse generator is similar in design as a system described in Ref. 16.

The voltage pulse generated with this system is shown in Fig. 1. It has a full width at half maximum (FWHM) of 20 ns and a rise and fall time of 10 ns. The pulse was applied to a dc microhollow cathode discharge in 400 Torr xenon. The sustaining dc voltage was 230 V and the dc current was 1 mA. The voltage across the discharge was measured by means of a voltage probe (TEK5100) and the current through the discharge was measured by means of a current viewing resistor of 50 ohm in series with the discharge. The pulsed electric field causes an instantaneous increase in electron density, which after the pulse decays through recombination with a time constant of several microseconds.[13] The drop in discharge voltage from 230 V to approximately 110 V after the pulse, and the following recovery to the dc sustaining voltage, the beginning of which is only shown in Fig. 1, is related to the temporal development in electron density.

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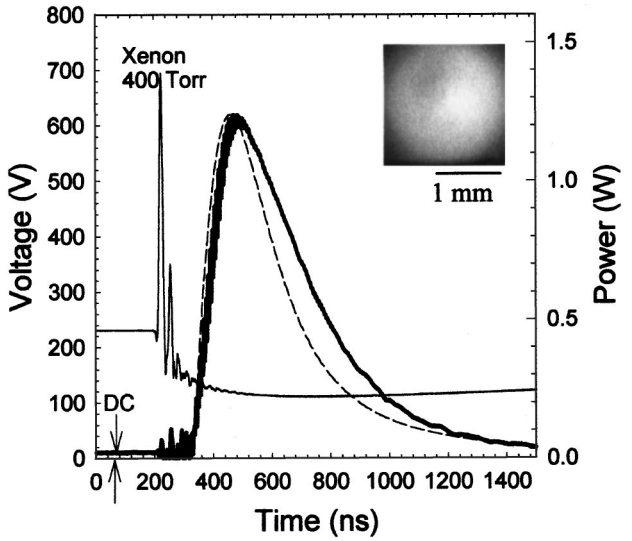

FIG. 1. Temporal development of voltage across the microhollow cathode discharge and the corresponding xenon excimer emission at 172 nm is shown. The voltage before pulse application (<200 ns) is the sustaining voltage of the dc discharge. After pulse application, the discharge voltage drops to 110 V and approaches the dc value after several microseconds. The solid bold line represents the temporal development of measured excimer emission. The dc value of the excimer power (indicated by DC) is less than 2% of the peak power. The dashed line represents the modeling results. An end-on image of the excimer source with the 100 μm diameter microhole located in the center is shown in the insert.

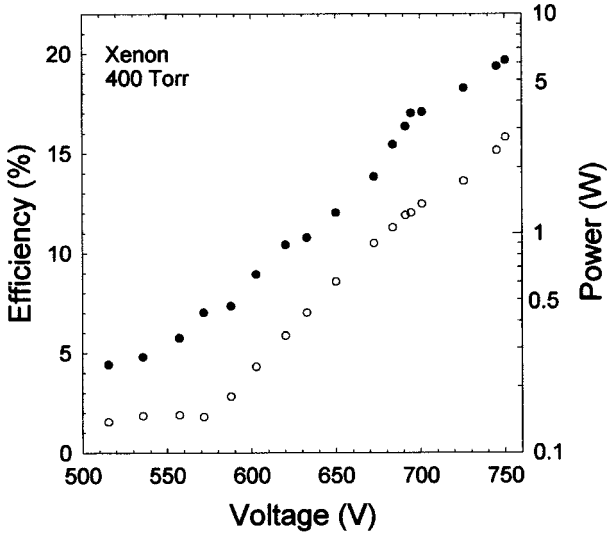

FIG. 2. Optical power in the VUV (at the center wavelength of 172 nm) and corresponding excimer efficiency versus pulse voltage is shown. Whereas the optical power increases exponentially, the efficiency increases linearly with pulsed voltage.

Also shown in Fig. 1 is the temporal development of the excimer emission at 172 nm, the peak in the second xenon excimer continuum. The VUV radiation was spectrally resolved by means of a McPherson 302 monochromator and recorded with a photomultiplier tube (PMT) (Hamamatsu R1533). Measurements of the spectral distribution showed that the line profile was not affected by the electrical pulse. Therefore, the radiation at 172 nm is representative of the total optical power in the VUV. The measured excimer emission signal is delayed with respect to the electric pulse. This was found to be due to the time delay of the PMT, which was measured as 50 ns. The peak in excimer emission is at approximately 200 ns after the electrical pulse application. The FWHM of the excimer pulse is 350 ns, the decay time constant (1/*e* decay time) is 320 ns, both independent of pulse amplitude.

The excimer intensity following pulse application stays at a constant value, the dc excimer emission, up to pulsed voltages of 500 V. Increasing the amplitude from 500 to 750 V caused an exponential increase in peak intensity, doubling every 45 V. The absolute values of the optical power of the excimer pulse were obtained by measuring the excimer intensity at 1 mA dc with a calibrated detector,[6] and by relating this value to the values obtained in the pulsed mode (Fig. 1). Peak optical power is plotted versus peak voltage of the pulse in Fig. 2. Largest values are 2.75 W at a pulsed voltage of 750 V emitted from a single microhollow cathode discharge.

The efficiency, defined as the ratio of optical energy to electrical energy is plotted in Fig. 2 versus voltage. The electrical energy was obtained by integrating over the temporal development of the product of voltage and current from the application of the voltage pulse to the time where the excimer pulse had decayed to about 10% of its peak value. The efficiency decreases with increasing voltage up to 500 V from 8% to 4%. This is due to the fact that in this voltage range the effect of the pulse on the excimer emission is negligible, but not the dissipated pulsed electric energy. Above 500 V, the efficiency increases linearly with voltage, and reaches 20% at an applied pulsed voltage of 750 V, the largest voltage which our pulse generator provided.

Although the optical power increases exponentially, by a factor of 18 (0.15 to 2.75 W) from 550 to 750 V pulse amplitude, the time averaged radiant emittance of the source rises only by a factor of 2.5 (from 5.9 to 15.2 W/cm^2). This is due to the fact that with increasing voltage and current, the area of the source expands.[10] The diameter of the emitting area increases from 0.9 to 2.4 mm when the pulse amplitude is increased from 550 to 750 V. This was observed by means of a high speed camera (Princeton Instrument ICCD-MAX system), with a variable shutter time. For these measurements, the shutter time was set at 300 ns, centered right at the time when the excimer emission peaked. A VUV filter (with a peak transmission of 24% at 170.9 nm and a FWHM of 26.8 nm) was used to block any radiation except that of the excimer radiation. Shown as an insert in Fig. 1 is a VUV image of the excimer source at a pulse voltage of 700 V. It covers an area of 2.14 mm^2, very large compared to the size of microhole. The 100 μm diameter cathode hole is located in the center of the luminous area.

The strong increase in optical power and the increase in efficiency can be explained by nonequilibrium effects in the discharge plasma. Calculations and measurements in air plasmas with similarly short pulses applied indicate that the nanosecond pulses cause electron heating without affecting the gas temperature.[13] This shift in electron energy causes a nonlinear increase in the rate coefficient for excitation of the xenon atoms, the precursors of the excimers. This nonequilibrium effect can be expected as long as the pulse duration and pulse amplitude, correspondingly the electrical energy dissipated in the plasma is small enough that glow-to-arc transitions can be avoided.

The observed temporal response of the excimer emission to the 20 ns pulse (Fig. 1) is consistent with experimental and theoretical results obtained on barrier discharges. We have used a model by Adler and Müller[17] to model this response. It is a rate equation model which includes the rate equations for xenon atomic ions (Xe^+), xenon molecular ions (Xe_2^+), xenon metastable atoms [$Xe(^3P_2)$], vibrationally excited excimers [$Xe(1_u, v \gg 0)$], corresponding to the first continuum emission, and vibrationally relaxed excimers [$Xe(1_u, v \approx 0)$], corresponding to the second continuum emission. Data on the densities of the various excited and ionized species in direct current microhollow cathode discharges, which serve as initial conditions for the rate equations, are not yet available. Consequently, we have used estimates for the electron and the ionized species densities based on measured electrical discharge parameters, and estimates for the excited species densities based on measured excimer emission. The estimated values were $Xe^+ = 10^{14}/cm^3$, $Xe_2^+ = 10^{13}/cm^3$, $Xe(^3P_2) = 4 \times 10^{13}/cm^3$, $Xe(1_u, v \gg 0) = 4 \times 10^{11}/cm^3$, and $Xe(1_u, v \approx 0) = 4 \times 10^{11}/cm^3$. The result of this rather rudimentary calculation is shown in Fig. 1 (dashed curve). The rise of the excimer emission is determined by three-body collisions, forming the dimer, and the fall by dimer decay processes.

The voltage is at this point limited by the available semiconductor switch, but the use of fast, higher voltage semiconductor switches, or the use of plasma switches such as sparkgaps promise to drive the microhollow cathode discharges to computed, and in barrier discharges observed, higher values of efficiency. The simplicity of the microhollow cathode geometry, the fact that compact, inexpensive semiconductor switches can be used in drivers for pulsed microhollow cathode discharge excimer lamps, the possibility to generate them in arrays, the demonstrated high efficiency, and the high power density (15.2 W/cm^2 in this case) makes microhollow cathode discharge excimer lamps attractive for industrial applications.

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