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Optimizing drive parameters of a nanosecond, repetitively pulsed microdischarge high power 121.6 nm source

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Abstract

Utilizing nanosecond high voltage pulses to drive microdischarges (MDs) at repetition rates in the vicinity of 1 MHz previously enabled increased time-averaged power deposition, peak vacuum ultraviolet (VUV) power yield, as well as time-averaged VUV power yield. Here, various pulse widths (30–250 ns), and pulse repetition rates (100 kHz–5 MHz) are utilized, and the resulting VUV yield is reported. It was observed that the use of a 50 ns pulse width, at a repetition rate of 100 kHz, provided 62 W peak VUV power and 310 mW time-averaged VUV power, with a time-averaged VUV generation efficiency of $\sim 1.1\%$. Optimization of the driving parameters resulted in 1–2 orders of magnitude increase in peak and time-averaged power when compared to low power, dc-driven MDs.

Keywords: microdischarge, pulsed discharge, vacuum ultraviolet, gas discharge

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

1. Introduction

Ever-growing demand for higher communication speeds and increased computational power is driving aggressive research dedicated to advancing semiconductor fabrication techniques. Photolithography is a critical topic of such research, where the well-known relation for minimum fabrication dimensions is $D_{\min} \propto \lambda$, where λ is the wavelength of interest. For this reason, the use of low wavelength light sources such as KrF* (248 nm), ArF* (193 nm) or F₂* (157 nm) excimer lasers represent the present state-of-the-art sources for industrial photolithography processes. Obviously, use of even lower wavelengths would allow for even higher fabrication resolution. This manuscript reports the optimization of a 121.6 nm microdischarge vacuum ultraviolet (MD-VUV) light source, generated by Lyman- α (L_{α}) emission from atomic hydrogen. Such a device holds a unique status for VUV photolithography sources as 121.6 nm occupies essentially the lowest usable wavelength for optics systems, due to the fact that the best VUV optics (LiF and MgF₂) will not transmit light below wavelengths of ~ 115 nm. Additional applications of

UV/VUV sources include the direct photo-ionization of gases [1], energy efficient triggering of undervoltaged spark gaps [1], and sanitation and purification [2, 3]. Other applications may be found in high pulse repetition rate triggering of photoconductive solid-state switches, possibly replacing other pulsed light sources at longer wavelengths [4].

Here, the device previously reported in [5, 6] is evaluated in detail. The primary focus of this study is the optimization of an argon–hydrogen gas mixture to produce strong L_{α} emission. Since neon–hydrogen gas mixtures were previously reported to produce intense L_{α} emission [7], the results of an additional study using such a gas mixture are addressed as well. Unless otherwise noted, a (99%/1%) argon–hydrogen gas mixture was used at a pressure of 100 Torr (13.3 kPa).

While MDs driven by nanosecond timescale pulses are of significant interest to the scientific community, little work has been directed towards the use and optimization of MDs driven by repetitive pulses at high repetition rates. Martin *et al* report the use of pulse repetition rates up to 150 kHz to deliver up to 37 W to a MD load [8]. Here pulse full width at

Figure 1. Experimental apparatus with diagnostics and MD geometry.

half maximums (FWHM) from 30–250 ns, and pulse repetition rates from 100 kHz–5 MHz are used to drive the MD. The performance of the MD-VUV source, including peak VUV power, time-averaged VUV power, time-averaged efficiency, and spectral impurity content are all reported.

2. Experimental setup

A cross sectional overview of the experimental setup and MD geometry is depicted in figure 1. The MD geometry is constructed from a direct bonded copper substrate with 125 μm copper electrodes on opposing sides of a 250 μm thick Al_2O_3 dielectric. A single, 400 μm diameter hole is drilled through the entire substrate, producing the structure shown in figure 1, most commonly referred to as the microhollow cathode discharge (MHCD). To minimize the load capacitance a chemical etch process is used to remove excess copper on the anode side of the MD structure. During this fabrication process, the structure is subjected to many potential sources for impurities. For this reason, a rigorous cleaning process is performed to minimize impurities which have significant impact on the spectral quality of the MD-VUV source. After a series of ultrasonic cleaning processes using common industrial cleaning solutions, a final ultrasonic cleaning process in methanol is used. The MD is then moved to an RF plasma oven where a 50%/50% argon/oxygen gas mixture is used to remove remaining hydrocarbons. Once complete, a pure argon gas is used in the RF plasma oven to remove oxides produced during the previous cleaning process. The final cleaning process involves securing the MD structure to the experimental apparatus and performing a low power (~ 1 W) dc ‘burn-in’ in pure argon varied from 50–800 Torr. During the first 60–120 s, impurities from hydrogen (121.6 nm) and oxygen (130.2 nm and 130.5 nm) are clearly present in the 115–150 nm region. Within a few minutes, these impurities

Figure 2. (a) Voltage and current waveforms for different pulse lengths at 1 MHz pulse repetition rate. (b) MD voltage versus time for 50 ns pulse width at pulse repetition rates of 100 kHz and 1 MHz demonstrating the earlier collapse and lower potential achieved with higher pulse repetition rate.

significantly decrease with hydrogen being completely absent from the spectra. After roughly 10 min the burn-in process is complete, and the broad 127 nm Ar_2^* excimer emission is the primary component in the 115–150 nm region. Even still, minor contribution from the oxygen impurity is still present. It is possible that this oxygen is a product of ablation and evaporation processes on the Al_2O_3 dielectric, as is suggested by Moselhy *et al* [9].

To drive the MD, a single SiC, high voltage MOSFET is employed to directly switch the potential from a capacitor bank onto the MD anode, see figure 1. With this configuration, the MOSFET is responsible for both the turn on and turn off time of the delivered pulse. Thus, the pulse width is easily adjustable, although delivering short pulses in a high side driver configuration requires additional consideration. To gate the MOSFET, floating potential, high speed power electronics are utilized, which enable pulse widths as low as 30 ns, see figure 2(a). By directly switching the potential to the MD load, the source impedance of the high voltage pulser is significantly reduced when compared to pulse forming line (PFL) configurations. This results in better energy coupling at as the MD impedance may drop dynamically to values well below 50 Ω . Additionally this system may be used to provide a series of pulses in burst mode at repetition rates in excess of 10 MHz, allowing for time-averaged power delivery in excess of 1 kW to the MD load (see figure 3(a)).

Figure 3. Time-averaged power deposited into the MD load versus pulse width for different pulse repetition rates.

Additional studies not detailed here involved the development of a PFL based high voltage pulser. Using a self-matched transmission line based pulse generator [10, 11] combined with a two line, transmission line transformer [12] for voltage step-up, load voltages of up to 1 kV with pulse widths down to 8 ns were produced. This pulser was successfully rep-rated at 1 MHz by pulse charging the PFL. It had the distinct advantage over the hard switching approach that the pulse terminated itself without having to actively turn off the switch. However, the PFL based pulser carried an increased output impedance over the MOSFET pulser such that the delivered power to the load was significantly lower; roughly below 20 W for an output impedance of 100 Ω . In comparison, the MOSFET based pulser has an output impedance of roughly 1 Ω at low current and 20 Ω at peak current. Hence, when VUV yield is of interest, it was observed that the direct MOSFET switching pulser provided superior performance to the PFL configuration solely due to the ability to deliver significantly higher power (1 + kW).

The time necessary to amplify a background density of electrons n_0 to a critical density n_{crit} (i.e. the formative time) can be approximated as $\tau_f \sim \ln(n_{\text{crit}}/n_0)/\nu_{\text{iz}}$ where τ_f and ν_{iz} are the formative time and ionization rate, respectively [13]. For pulse widths exceeding the formative delay time, a collapse in the potential is observed, corresponding to the development of a high electron density and consequently low impedance discharge. By applying higher pulse repetition rates, residual pre-ionization decreases the formative time, thus decreasing the sustainable pulse width. This effect is demonstrated in figure 2(b), where it can be seen that pulses at 100 kHz repetition rates achieve higher potential and experience a collapse in potential much later than pulses applied at a 1 MHz pulse repetition rate.

An evacuated ($\sim 10^{-6}$ Torr) VUV spectrograph is used for both measuring spectral content and VUV power [14]. Whereas previous versions of this system utilized MgF₂ focusing lenses [15], this system makes use of a series of focusing mirrors which eliminate chromatic aberration associated with a lens setup. The power is calculated applying the known solid angle of the spectrograph and efficiency of the spectrograph and treating the MD as a point source with spherically isotropic emission, as is common in MD-VUV studies [16]. The power measured by the VUV spectrograph

Figure 4. Time-averaged VUV power (at L_{α} only) versus pulse width for different pulse repetition rates using an Ar-H₂ (99%/1%) gas mixture at 100 Torr. Error bars shown for the 5 MHz condition are characteristic to each pulse repetition rate.

was found to be within 10% of the value measured using a VUV calibrated photodiode.

3. Experimental results

3.1. Time-averaged input power

It can be reasonably assumed that higher power delivered to the load will result higher power yielded from the VUV emission, given that the efficiency is not significantly decreased. For this reason, the ability to deliver higher power to the MD load is desirable. The power delivered is plotted versus pulse width for different pulse repetition frequencies. Using a pulse width of 30 ns and a pulse repetition rate of 100 kHz, only 17.2 W time-averaged power is delivered to the MD load. Alternatively, whenever a 150 ns pulse width and 5 MHz pulse repetition rate are applied, a time-averaged power delivery of 1.04 kW is achieved.

3.2. Time-averaged VUV power

The influence of pulse width and pulse repetition rate on time-averaged VUV power is given in figure 4. Note that this is the power, only at L_{α} , not including the power radiated from any impurities present in the system. Longer pulse width results in overall higher power delivered by the source for a given pulse repetition rate (see figure 3). In general higher input power provides higher VUV power, however, at some non-constant efficiency. Still, for a given repetition rate, increased pulse width increases the time-averaged VUV power. Notably, time-averaged power VUV power in excess of 3 W was measured for 1 MHz rep-rate and 250 ns pulse width, and 5 MHz and 150 ns pulse width. The device reported here demonstrates obvious advantage when compared with a similar 128 nm deep VUV, argon excimer MD-VUV sources where time-averaged VUV power is in the vicinity of 30 mW [17] (i.e. 2 orders of magnitude higher power).

3.3. Peak VUV power

The characteristic lifetime of the excited L_{α} radiating state is ~ 1.6 ns, thus the VUV emission almost directly follows

Figure 5. Peak VUV power (at L_α only) versus pulse width for different pulse repetition rates using an Ar–H₂ (99%/1%) gas mixture at 100 Torr. Error bars shown for the 100 kHz condition are characteristic to each pulse repetition rate.

Figure 6. Time-averaged efficiency of VUV generation (at L_α only) versus pulse width for different pulse repetition rates using an Ar–H₂ (99%/1%) gas mixture at 100 Torr. Error bars shown for the 100 kHz condition are characteristic to each pulse repetition rate.

the excitation waveform. This has been confirmed using temporally resolved photomultiplier tube diagnostics on the L_α emission [5]. The peak VUV power can be approximated from the time-averaged VUV power and the duty cycle of the driving source. The peak VUV power at L_α alone is given in figure 5.

In regards to peak VUV power, the 100 kHz is clearly superior, achieving 62 W peak power for a 50 ns pulse width. Significant peak power, 30–40 W is also demonstrated by the 500 kHz and 1 MHz pulse repetition rates. Previously, peak VUV power of a nanosecond timescale pulsed Ar₂^{*} MD-VUV source was reported to be 180 mW [17]. Again, this device provides in excess of 2 orders of magnitude improvement. This can be partially attributed to the higher Einstein coefficient of spontaneous emission for the L_α radiator when compared to Ar₂^{*} sources where nanosecond pulses produce microsecond timescale Ar₂^{*} emission [17].

3.4. Time-averaged efficiency

Figure 6 shows the time-averaged efficiency versus pulse width for various pulse repetition rates. Again, the 100 kHz pulse repetition rate demonstrates superior performance, achieving in excess of 1% efficiency. This is a consequence of the

Figure 7. Experimental spectra of the MD-VUV source in the deep VUV regime for different pulse widths and a 100 kHz pulse repetition rate in using an Ar–H₂ (99%/1%) gas mixture at 100 Torr.

extended formative delay time corresponding to 100 kHz pulse repetition rates. That is, due to the longer time between pulses, lower plasma density remains as the background initial condition for the following pulse. As is demonstrated in figure 2(b), this allows the MD to sustain a voltage for a longer period of time, and achieve higher peak voltage. Higher voltage results in higher reduced electric field E/N , where E is the electric field and N is the density of the neutral gas. Higher E/N corresponds to higher excitations rates, and less energy lost to elastic collisions with the background [18]. Hence, the overall superior efficiency of the 100 kHz pulse repetition rate can be credited to the fact that at 100 kHz the higher voltage is sustained for a longer period of time. Alternatively, higher repetition rates correspond to an earlier collapse in potential and lower VUV generation efficiency, particularly for the 5 MHz repetition rate.

While the device discussed here demonstrated superior performance regarding peak and time-averaged VUV power, inferior VUV generation efficiency is demonstrated. For similar deep VUV MD-VUV sources, efficiencies as high as 5–6% were reported [17] albeit at lower power. It should also be noted that Xe₂^{*} (172 nm) MD-VUV sources have demonstrated as high as 20–30% efficiency when driven by nanosecond timescale pulses at lower power [19–21]. However for many applications such as photolithography, a 172 nm device only holds modest advantage over existing systems. Ultimately, when considering the power gains, the inferior performance regarding efficiency may be considered tolerable.

3.5. Impurity content

Figures 7 and 8 demonstrate the spectral impurity content in the deep VUV region for different pulse widths for 100 kHz and 1 MHz respectively. Note that the FWHM of the apparatus profile of the VUV spectrograph is quite large as a result of

Figure 8. Experimental spectra of the MD-VUV source in the deep VUV regime for different pulse widths and a 1 MHz pulse repetition rate using an Ar-H₂ (99%/1%) gas mixture at 100 Torr. The bottom panel is a theoretical spectrum generated using SPECTRAPLOT [14] to calculate the spectra of C I, C II, C III, N I, O I, H I. Simulated relative intensities of each species are scaled independently as the species volume fraction is unknown.

intentionally setting the entrance slit width to 50 μm for these experiments, resulting in a $\sim 0.6\text{ nm}$ apparatus profile. This maximizes the photon count of the VUV diagnostics at the expense of spectral resolution. As a result, much broader lines are observed in figures 7 and 8 when compared to figure 9 where the apparatus profile was minimized to preserve spectral resolution.

The primary impurities observed are from oxygen, nitrogen, and carbon. Oxygen and nitrogen are present for every experimental condition, not just when high power deposition is used, suggesting that the source of the oxygen and nitrogen is residual gas, remaining from when the MD chamber is evacuated. It is also possible that oxygen could be generated by evaporation and ablation processes on the dielectric, or from H₂O impurities in the chamber. Alternatively, carbon based impurities are only prevalent when high excitation power is used (i.e. higher pulse repetition rate and longer pulse width). This suggests that carbon is present on the MD structure and is evaporated or ablated from the MD structure when the higher power excitation is utilized. Carbon impurities could remain from carbon deposition during the drilling process, hydrocarbons used while machining, chemicals used during the etch process etc. Lifetime characterization of the MD is necessary to determine whether the observed impurities are stable and reproducible over extended periods of time. At this time, such a study has not been completed.

In addition to the experimental spectra, a theoretical spectrum generated using SPECTRAPLOT [14] is also given in figure 8. An electron temperature of 3.5 eV was used to generate the spectra. This temperature was previously

Figure 9. Comparison of 50 Torr Ne-H₂ (99.7%/0.3%) and Ar-H₂ (99.7%/0.3%) MD-VUV spectra in the deep VUV regime driven with high power ($\sim 550\text{ W}$), 80 ns pulse width, 80 A, 1 MHz pulse repetition frequency. Ne-H₂ produced 1 W time-averaged power (at L $_{\alpha}$ only), 12.4 W peak (at L $_{\alpha}$ only), with a time-averaged efficiency of 0.19%. Ar-H₂ produced 3.4 W time-averaged power (at L $_{\alpha}$ only), 42.8 W peak (at L $_{\alpha}$ only), with a time-averaged efficiency of 0.63% (These experiments used a 380 μm thick Al₂O₃ dielectric).

estimated using optical emission spectroscopy [6], but the exact value has little influence on the spectra shown in figure 8. The theoretical spectra given in figure 8 were generated by simulating the C I, C II, C III, N I, O I and H I spectra and simply amplitude scaling the contribution of each species to account for the unknown volume fractions. It is concluded that virtually all observed features in the measured spectra are simply due to emissions from atomic carbon, nitrogen, oxygen, and hydrogen; also including the singly and doubly ionized states of carbon. For pulse widths below 100 ns, the 121.6 nm L $_{\alpha}$ emission is the dominant contributor to the emission spectra. For pulses above 100 ns, the 100 kHz experiments demonstrate strong impurity content, but L $_{\alpha}$ is still the primary contributor in the deep VUV regime. Alternatively, for pulses above 100 ns, the 1 MHz experiments demonstrate significantly inferior performance as carbon lines begin to dominate the spectrum.

While the spectrum suffers from spectral impurities, it should be noted that narrow pass band L $_{\alpha}$ filters are commercially available. The application of such a device would resolve possible issues arising from spectral impurities.

3.6. Neon-hydrogen versus argon-hydrogen

Neon-hydrogen gas mixtures have attracted significantly more attention than argon-hydrogen mixtures for the generation of L $_{\alpha}$ radiation. Using $\sim 1\text{ W}$, dc excitation in a Ne-H₂ gas at 50 Torr, L $_{\alpha}$ radiation was successfully generated. Additional studies using a Ne-H₂ gas mixture under high input power ($\sim 550\text{ W}$) was also conducted, see figure 9. When subjected to higher power deposition, the Ne-H₂ gas mixture demonstrated inferior performance to the Ar-H₂ gas mixture in regards to time-averaged and peak VUV power yield, time-averaged efficiency, and spectral purity.

4. Conclusions

Optimization of the pulsed power driving parameters for a MD-VUV source is presented. Specifically, the influence of the source pulse width and pulse repetition frequency on peak and time-averaged VUV power, VUV generation efficiency, and spectral impurity content was studied. Notable performance was obtained using the 100 kHz, 50 ns pulse width parameter where the peak VUV power was measured to be 62 W, with 310 mW time average power and a time-averaged VUV generation efficiency of 1.1% with minimal spectral impurity. Similarly, using the 1 MHz, 50 ns pulse width the peak VUV power was measured to be 35 W, with time average power of 1.8 W, produced at an efficiency of 0.75%, with minimal spectral impurity. Note that using a similar driving source for an Ar-H₂ MD-VUV source and an 80 ns pulse width at 1 MHz repetition rate, the time average and peak VUV power were measured to be 3.4 W and 43 W respectively, generated at ~0.63% efficiency [5].

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